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Original Research Paper

Production of Green Hydrogen from Renewable Energy for Refinery Applications: A Pathway toward Decarbonising Petroleum Refining

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Abstract

The petroleum refining sector is one of the largest industrial users of hydrogen in the world. It mostly gets its hydrogen from steam methane reforming (SMR), which is a process that releases a lot of greenhouse gases. As climate policies around the world get stricter and businesses look for long-term ways to cut carbon emissions, green hydrogen made by water electrolysis powered by renewable energy sources has become a promising option. This study examines the technical, economic, and environmental feasibility of producing green hydrogen from renewable energy for refinery applications. A systematic review of contemporary literature was combined with a techno-economic assessment framework to evaluate renewable-powered electrolysis technologies and their integration into refinery operations. Findings indicate that green hydrogen can significantly reduce carbon emissions associated with hydroprocessing and desulfurisation units while supporting broader energy transition objectives. However, challenges remain regarding capital costs, renewable energy intermittency, electrolyser efficiency, and infrastructure requirements. The study concludes that despite current economic barriers, declining renewable electricity costs, technological advancements in electrolysis, and supportive policy frameworks are accelerating the viability of green hydrogen adoption in petroleum refineries. The transition from grey hydrogen to green hydrogen represents a critical strategy for achieving net-zero emissions within the refining sector.

Keywords: green hydrogen, renewable energy, electrolysis, petroleum refineries, decarbonisation, energy transition.

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1. INTRODUCTION

Hydrogen plays a critical role in petroleum refining, particularly in hydrocracking, hydrotreating, and desulfurisation processes that improve fuel quality and comply with environmental regulations. Traditionally, refineries produce hydrogen through steam methane reforming (SMR), a process that relies on natural gas and contributes significantly to carbon dioxide (CO_2) emissions. The growing urgency to mitigate climate change has intensified efforts to identify cleaner alternatives for industrial hydrogen production.

Green hydrogen, defined as hydrogen generated through water electrolysis powered entirely by renewable energy sources such as solar and wind power, has emerged as a promising solution for reducing industrial emissions. Unlike grey hydrogen derived from fossil fuels, green hydrogen produces minimal greenhouse gas emissions throughout its lifecycle and can contribute significantly to industrial decarbonisation (Gómez & Castro, 2024). Recent advances in electrolyser technologies and declining renewable electricity costs have improved the prospects for large-scale green hydrogen deployment.

Petroleum refineries serve as an ideal initial market for green hydrogen due to the extensive use of hydrogen in existing operations. Major energy companies, including Shell, BP, and Ecopetrol, have initiated green hydrogen projects aimed at decarbonising refinery operations.

This paper investigates the potential of renewable-energy-based green hydrogen production for refinery applications, evaluates technological pathways, examines economic feasibility, and discusses the implications for sustainable petroleum refining.

Research Objectives

The study aims to:

1. Examine the technologies used in green hydrogen production.
2. Assess the integration of renewable energy-powered electrolysis into refinery operations.
3. Evaluate the economic and environmental benefits of green hydrogen adoption.
4. Identify challenges and future opportunities for large-scale implementation.

2. LITERATURE REVIEW

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2.1 Hydrogen Production Pathways

Hydrogen can be produced through several technological pathways, each characterised by different feedstocks, energy sources, environmental impacts, and economic considerations. The most widely recognised classifications are grey hydrogen, blue hydrogen, and green hydrogen. Grey hydrogen is produced from fossil fuels, primarily natural gas, through steam methane reforming (SMR), whereas blue hydrogen incorporates carbon capture and storage (CCS) technologies to reduce carbon emissions. Green hydrogen is generated through water electrolysis powered by renewable energy sources such as solar and wind energy (Jumah, 2024).

The distinction among these production pathways is important because the environmental performance and long-term sustainability of refinery operations are directly influenced by the source of hydrogen used. Table 1 presents a comparative overview of the major hydrogen production pathways

Table 1: *Comparison of Hydrogen Production Technologies*

Parameter	**Gray Hydrogen (SMR)**	**Blue Hydrogen (SMR + CCS)**	**Green Hydrogen (Electrolysis)**
Feedstock	Natural Gas	Natural Gas	Water
Energy Source	Fossil Fuel	Fossil Fuel + CCS	Renewable Energy
Carbon Emissions	High	Moderate	Very Low
Technology Maturity	High	High	Medium–High
Production Cost	Low	Medium	High
Sustainability	Low	Moderate	High

Source: Adapted from Wang et al. (2024); Zhang et al. (2024).

As shown in Table 1, grey hydrogen remains the most economically competitive production pathway due to its mature technology and established infrastructure. However, it exhibits the highest carbon emissions, making it inconsistent with global decarbonisation objectives. Blue hydrogen offers an intermediate solution by reducing emissions through carbon capture technologies, although residual emissions remain a concern. In contrast, green hydrogen demonstrates the strongest environmental performance because it utilises renewable electricity and water as its primary inputs.

The comparison further reveals that although green hydrogen currently has higher production costs, its sustainability advantages position it as the preferred long-term solution for industrial sectors seeking carbon neutrality. Consequently, many refineries are increasingly evaluating green hydrogen as a replacement for conventionally produced hydrogen.

2.2 Electrolysis Technologies for Green Hydrogen Production

The production of green hydrogen depends largely on electrolysis technologies capable of efficiently converting renewable electricity into chemical energy. Three major electrolyser technologies dominate current research and commercial deployment: Alkaline Electrolysers (AEL), Proton Exchange Membrane Electrolysers (PEM), and Solid Oxide Electrolysers (SOEC).

Each technology differs in terms of efficiency, operational flexibility, cost, and technological maturity. These differences hold particular significance for refinery applications, as continuous hydrogen supply is essential despite fluctuations in renewable energy generation. Table 2 summarises the key characteristics of the major electrolyser technologies..

Table 2: *Characteristics of Major Electrolyzer Technologies*

Technology	Efficiency (%)	Operating Temperature	Advantages	Limitations
Alkaline Electrolyzer	60–70	60–90°C	Mature, low cost	Slow response
PEM Electrolyzer	65–75	50–80°C	Flexible operation, high purity hydrogen	Higher capital cost
SOEC	80–90	700–1000°C	High efficiency	Commercial immaturity

Source: Nnabuife et al. (2025).

Table 2 indicates that PEM electrolysers provide the most suitable operational characteristics for integration with intermittent renewable energy systems. Their ability to rapidly adjust hydrogen production rates allows them to respond effectively to fluctuations in solar and wind power generation. Alkaline electrolysers, although less flexible, remain attractive due to their lower capital investment requirements and established industrial track record.
SOEC technology exhibits the highest efficiency among the three alternatives; however, challenges related to high-temperature operation and material durability have limited its widespread commercialisation. Therefore, current refinery projects primarily focus on PEM and alkaline electrolyser technologies as the most feasible pathways for large-scale green hydrogen production.

2.3 Hydrogen Demand in Petroleum Refineries

Hydrogen is indispensable in modern refineries for hydrocracking and hydrotreating processes. Increasingly stringent fuel standards have elevated refinery hydrogen demand worldwide. Historically, approximately one-quarter of global hydrogen consumption has been associated with refinery operations.

The transition to green hydrogen provides refineries with an opportunity to reduce operational emissions while maintaining production efficiency. Shell's Refhyne II project in Germany and BP's European hydrogen initiatives demonstrate growing industry interest in renewable hydrogen integration.

2.4 Environmental Benefits

Green hydrogen offers substantial environmental advantages over conventional hydrogen production. Lifecycle analyses indicate that replacing SMR-derived hydrogen with renewable hydrogen can reduce carbon emissions by up to 90% depending on electricity sources and operational configurations. Green hydrogen also contributes to reduced methane emissions associated with natural gas extraction and transportation.

2.5 Economic Challenges

Despite environmental benefits, green hydrogen remains pricier than conventional hydrogen. Major cost drivers include electrolyser capital expenditure, renewable electricity costs, and infrastructure investments. However, techno-economic analyses suggest that falling renewable energy prices and economies of scale could significantly reduce hydrogen costs by 2030–2050

3. METHODOLOGY

Research Design

This study employed a qualitative systematic literature review combined with a techno-economic assessment. Peer-reviewed journal articles, industry reports, and documented refinery case studies published between 2022 and 2025 were analysed.

Data Sources

Data were obtained from:

- International Journal of Hydrogen Energy
- Renewable Energy
- Energy Conversion and Management
- Energies
- RSC Advances
- Industry project reports from major refining companies

The selection criteria included relevance to green hydrogen production, renewable energy integration, refinery applications, and economic assessments.

Analytical Framework

The analysis focused on three key dimensions:

1. Technical feasibility
2. Economic viability
3. Environmental sustainability

Comparative evaluation was conducted between conventional hydrogen production through SMR and green hydrogen produced via renewable-powered electrolysis.

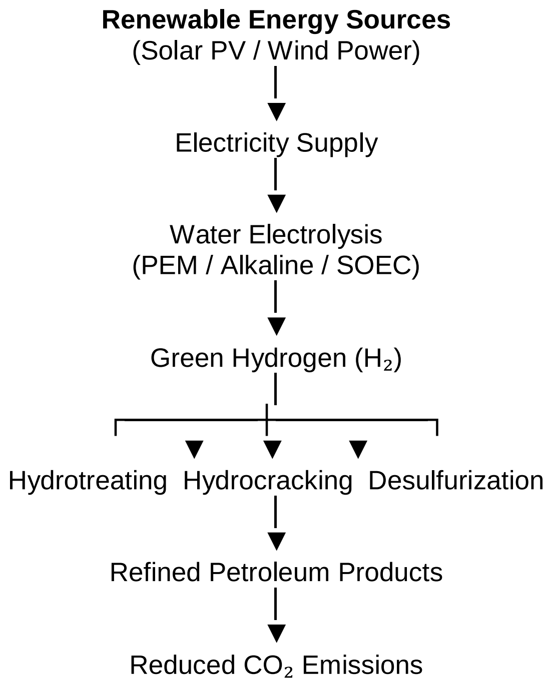

Figure 1: Conceptual framework showing the integration of renewable-energy-powered electrolysis for hydrogen production and utilization in refinery operations.

Figure 1 illustrates the conceptual framework underpinning green hydrogen production and its integration into refinery operations. The process begins with renewable energy sources, primarily solar photovoltaic (PV) systems and wind turbines, which generate electricity without producing greenhouse gas emissions. The generated electricity powers water electrolysis units that split water molecules into hydrogen and oxygen. The hydrogen produced is subsequently supplied to refinery processes such as hydrotreating, hydrocracking, and desulfurisation.

The figure demonstrates that renewable electricity serves as the critical link between clean energy generation and sustainable refinery operations. Unlike conventional hydrogen production through steam methane reforming, which relies on natural gas and emits substantial quantities of carbon dioxide, renewable-powered electrolysis produces hydrogen with minimal environmental impact. The framework, therefore, highlights how green hydrogen can support refinery decarbonisation while maintaining essential refining functions.

The conceptual pathway further illustrates the strategic importance of integrating renewable energy technologies with existing refinery infrastructure. Because refineries already possess hydrogen distribution and utilisation systems, the transition from fossil-fuel-derived hydrogen to green hydrogen can be achieved with fewer infrastructural modifications than would be required in sectors that currently lack hydrogen networks. This finding supports the argument that refineries represent one of the most practical and economically viable entry points for scaling the green hydrogen economy.

4. RESULTS

4.1 Technical Feasibility

4.4 Industrial Deployment and Refinery Applications

The growing adoption of green hydrogen within the petroleum refining industry demonstrates increasing confidence in the technology's technical and commercial viability. Several major energy companies have launched projects aimed at replacing conventionally produced hydrogen with renewable hydrogen generated through electrolysis. These projects vary in scale and geographical location but share a common objective of reducing refinery-related greenhouse gas emissions while supporting long-term sustainability goals.

To illustrate the current state of industrial implementation, selected refinery-based green hydrogen projects are presented in Table 4.

Table 4: *Selected Global Green Hydrogen Refinery Projects*

Company	Country	Project Capacity	Application
Shell (Refhyne II)	Germany	100 MW	Refinery Hydrogen Supply
BP	Spain/Europe	Multiple Projects	Refinery Decarbonization
Ecopetrol	Colombia	Pilot Scale	Refinery Operations
Neste	Finland	Developing	Renewable Fuel Production

Source: *Reuters industry reports (2024–2025).*

Table 4 presents examples of major green hydrogen projects currently being implemented within petroleum refineries across different regions of the world. The projects demonstrate the refining industry's increasing commitment to integrating renewable hydrogen into existing operations as part of broader decarbonisation strategies.

The table highlights that green hydrogen adoption has expanded beyond experimental or pilot-scale initiatives. For example, Shell's Refhyne II project in Germany represents one of the largest refinery-based electrolyser installations in Europe, with a planned capacity of 100 MW. Such large-scale deployment indicates growing confidence in the technical feasibility of renewable-powered hydrogen production for industrial applications. Similarly, BP's investment in multiple green hydrogen projects across European refineries reflects the strategic importance of hydrogen in achieving corporate net-zero emission targets.

Overall, the projects presented in Table 4 provide strong evidence that the petroleum refining sector is emerging as one of the leading industrial adopters of green hydrogen technology. The increasing scale and geographic distribution of these projects suggest that renewable hydrogen is transitioning from a promising concept to a commercially viable solution capable of supporting long-term refinery decarbonisation goals.

4.2 Environmental Performance

One of the primary motivations for adopting green hydrogen in petroleum refining is its potential to significantly reduce greenhouse gas emissions associated with hydrogen production. Conventional refinery hydrogen is predominantly produced through steam methane reforming, a process that generates substantial carbon dioxide emissions and contributes to climate change. In contrast, green hydrogen utilises renewable electricity and water, thereby minimising environmental impacts throughout the production cycle.

To evaluate the environmental implications of transitioning to renewable hydrogen, Table 3 compares key environmental performance indicators associated with conventional and green hydrogen production systems.

Table 3: *Environmental Performance Comparison*

Indicator	Conventional Refinery Hydrogen	Green Hydrogen
CO_2 Emissions	High	Near Zero
Methane Leakage Impact	Significant	Negligible
Renewable Energy Utilization	None	High
Compliance with Net-Zero Targets	Limited	Strong
Sustainability Rating	Low	High

Source: *Adapted from Gómez and Castro (2024).*

Table 3 demonstrates substantial environmental advantages associated with green hydrogen adoption. Carbon dioxide emissions show the most significant difference. Conventional hydrogen production through steam methane reforming releases significant amounts of greenhouse gases due to the use of natural gas as both feedstock and energy source. Conversely, green hydrogen produced through renewable-powered electrolysis generates minimal direct carbon emissions, making it an effective strategy for refinery decarbonisation.

The comparison further indicates that green hydrogen eliminates many of the environmental concerns associated with fossil fuel extraction and transportation, particularly methane leakage. Since methane possesses a higher global warming potential than carbon dioxide over shorter time horizons, reducing dependence on natural gas can contribute significantly to climate mitigation efforts.

Additionally, green hydrogen exhibits strong alignment with global net-zero emission targets and sustainability frameworks. As governments and international organisations continue to implement stricter environmental regulations, refineries utilising green hydrogen may be better positioned to comply with future carbon reduction requirements. Therefore, the findings suggest that environmental benefits constitute one of the strongest justifications for transitioning from conventional hydrogen production methods to renewable-based alternatives within the petroleum refining industry.

4.3 Economic Assessment

Current green hydrogen production costs remain higher than conventional hydrogen production costs. However, techno-economic reviews suggest that solar- and wind-powered electrolysis systems, combined with alkaline electrolysers, provide the most economically favourable configurations. Continued reductions in renewable energy costs are expected to narrow the cost gap significantly.

4.4 Industrial Deployment

Several large-scale projects demonstrate increasing commercial adoption:

- Shell's 100 MW electrolyser project at the Rheinland refinery in Germany.
- BP's planned hydrogen projects across European refining facilities.
- Ecopetrol's green hydrogen facility at the Cartagena refinery.

These initiatives illustrate growing confidence in green hydrogen's role in refinery decarbonisation strategies.

5. FINDINGS AND DISCUSSION

The findings of this study indicate that green hydrogen produced through renewable-energy-powered electrolysis has significant potential to transform petroleum refining into a more sustainable and environmentally responsible industry. The analysis of current literature, industrial projects, and technological developments demonstrates that green hydrogen can substantially reduce greenhouse gas emissions while supporting existing refinery operations. However, several technical, economic, and infrastructural challenges continue to influence the pace of adoption.

One of the most important findings is that green hydrogen technologies have reached a level of maturity that allows practical implementation within refinery environments. The review of electrolysis technologies revealed that both alkaline and proton exchange membrane (PEM) electrolysers are capable of producing hydrogen at scales suitable for industrial applications. While alkaline electrolysers offer lower capital costs, PEM systems provide greater operational flexibility and are particularly compatible with intermittent renewable energy sources such as solar and wind power. These characteristics make both technologies attractive options for refinery operators seeking to reduce their carbon footprint.

Environmental performance emerged as the strongest justification for green hydrogen adoption. The findings presented in Table 3 demonstrated that renewable hydrogen significantly outperforms conventionally produced hydrogen across all major environmental indicators. The transition from steam methane reforming to renewable-powered electrolysis has the potential to drastically reduce carbon dioxide emissions associated with refinery operations. Furthermore, green hydrogen eliminates many environmental concerns linked to fossil fuel extraction, transportation, and processing. As global climate policies become increasingly stringent, these environmental benefits are likely to become even more important for refinery competitiveness and regulatory compliance.

The analysis of global refinery projects presented in Table 4 further demonstrated that green hydrogen is transitioning from a conceptual technology to a commercially deployed solution. Major energy companies such as Shell, BP, and Ecopetrol have already initiated projects aimed at integrating renewable hydrogen into refinery operations. The geographical diversity of these projects indicates growing international confidence in hydrogen technologies and reflects the increasing role of renewable energy in industrial decarbonisation strategies. The evidence suggests that petroleum refineries are likely to remain among the leading sectors driving hydrogen market growth over the coming decades.

Despite these positive developments, economic considerations remain a significant challenge. The review identified renewable electricity costs, electrolyser capital expenditures, and hydrogen storage infrastructure as the primary factors contributing to the relatively high cost of green hydrogen production. At present, conventional hydrogen produced through steam methane reforming remains less expensive in many regions. Nevertheless, numerous studies predict substantial cost reductions as renewable energy deployment expands and electrolyser technologies continue to improve.

Figure 2 illustrates the projected reduction in green hydrogen production costs over the coming decades.

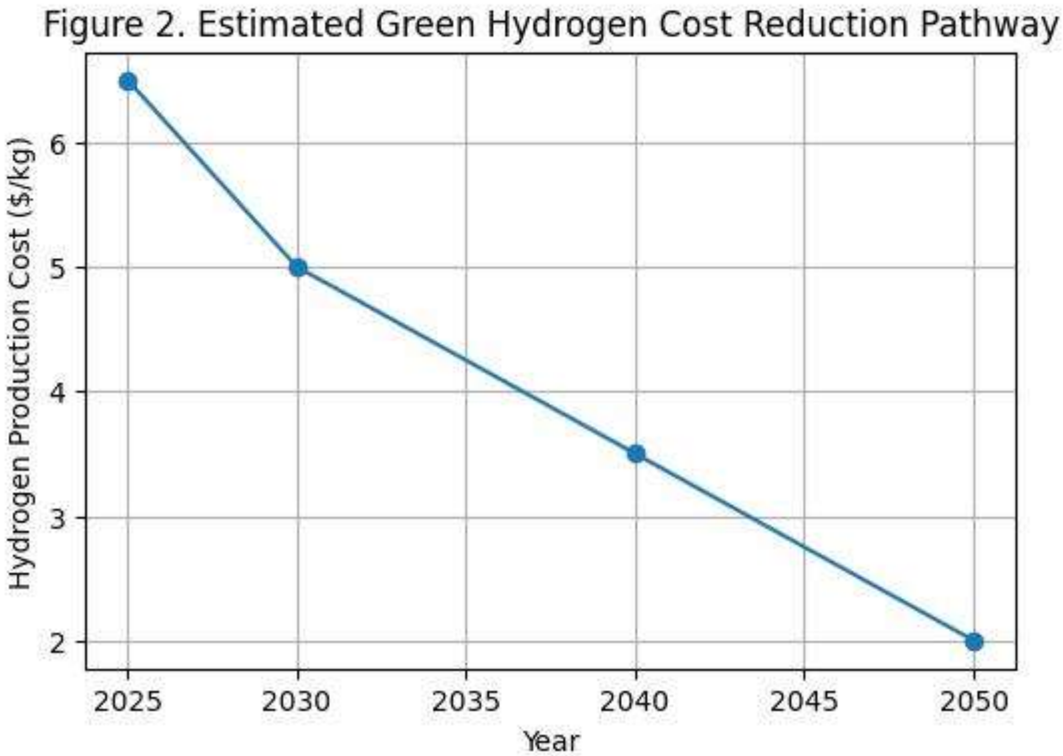

Figure 2: *Estimated Green Hydrogen Cost Reduction Pathway (2025–2050)*

The projected trend indicates a steady decline in green hydrogen costs between 2025 and 2050. Several factors contribute to this expectation, including decreasing costs of solar photovoltaic systems, expansion of wind power generation, technological improvements in electrolysers, and economies of scale associated with increased production capacity. As these developments continue, green hydrogen is expected to become increasingly competitive with conventional hydrogen production methods. Consequently, current investments in green hydrogen infrastructure should be viewed not only as environmental initiatives but also as strategic long-term economic investments.

The findings also reveal that the successful deployment of green hydrogen will depend heavily on supportive policy frameworks. Government incentives, carbon pricing mechanisms, renewable energy subsidies, and investments in hydrogen infrastructure can significantly improve project economics and accelerate industrial adoption. Countries that have implemented comprehensive hydrogen strategies have generally experienced faster project development and greater private-sector participation. Therefore, policy support remains a critical factor in determining the future growth of the green hydrogen sector.

Table 5 presents the major findings of this study, summarising the outcomes.

Table 5: *Summary of Key Findings*

Research Objective	**Key Finding**
Evaluate production technologies	PEM and alkaline electrolyzers are currently the most viable technologies
Assess refinery integration	Existing refinery infrastructure supports hydrogen integration
Examine environmental impacts	Green hydrogen significantly reduces greenhouse gas emissions
Analyze economics	High capital costs remain the principal barrier
Explore future opportunities	Declining renewable energy costs will improve competitiveness

Source: *Author's synthesis based on reviewed literature.*

Table 5 shows that the study successfully addressed all the research objectives established at the beginning. The findings confirm that refinery deployment is feasible with advanced green hydrogen production technologies and that existing refinery infrastructure can facilitate integration with minimal disruption. The analysis further established that environmental benefits represent the primary advantage of green hydrogen adoption, particularly in relation to greenhouse gas reduction and alignment with net-zero emission targets.

However, the study also confirms that economic barriers continue to limit widespread implementation. While green hydrogen currently faces cost disadvantages relative to conventional production methods, projected technological advancements and declining renewable energy costs are expected to improve economic viability significantly in the future. Therefore, the long-term outlook for green hydrogen remains highly positive.

Overall, the evidence reviewed in this study supports the conclusion that green hydrogen represents one of the most promising pathways for decarbonising petroleum refining. The combination of environmental benefits, technological feasibility, growing industrial adoption, and anticipated cost reductions suggests that renewable hydrogen will play an increasingly important role in the future of sustainable energy systems.

6. Conclusion

Green hydrogen produced through renewable-energy-powered electrolysis offers a viable pathway for reducing greenhouse gas emissions within petroleum refineries. The technology is technically feasible, environmentally beneficial, and increasingly supported by industrial stakeholders and policymakers. Although economic challenges remain, declining renewable energy costs and advances in electrolyser technology are expected to improve competitiveness over time.

Refineries constitute a strategic entry point for green hydrogen deployment due to their established hydrogen demand and infrastructure. The transition from grey hydrogen to green hydrogen can significantly contribute to achieving net-zero targets while maintaining refinery productivity and operational efficiency.

Future research should focus on optimising renewable-electrolyser integration, reducing production costs, improving hydrogen storage technologies, and evaluating large-scale commercial deployment under varying regulatory and market conditions.

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