International Journal of Multidisciplinary Research and Growth Evaluation.

Green Hydrogen and Low-Carbon Fuels: Shaping Nigeria's Industrial Decarbonization and Energy Future

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Article Info

ISSN (Online): 2582-7138
Impact Factor (RSIF): 8.04
Volume: 07
Issue: 01
Received: 18-11-2025
Accepted: 20-12-2025
Published: 22-01-2026
Page No: 517-522

Abstract
The global push for net-zero emissions has positioned green hydrogen and other low-carbon fuels as critical solutions for decarbonizing hard-to-abate industrial sector. This study examines the role of government policies and the potential of these fuels in shaping Nigeria's energy future and industrial decarbonization. Using a mixed-methods approach, including a survey of 147 staff from the Energy Commission of Nigeria (ECN) and inferential statistics, the research assesses perceptions of economic viability, infrastructural readiness, and necessary partnerships. While statistical analysis ($p < 0.05$) confirms that green hydrogen can significantly contribute to emission reductions, the findings reveal significant skepticism among stakeholders regarding its current economic viability (67.35% disagreement) and Nigeria's renewable energy capacity to support competitive production (63.26% disagreement). However, there is a strong consensus (78.87% agreement) on the indispensability of international partnerships. The study concludes that despite its potential, the development of a green hydrogen economy in Nigeria is hindered by high costs, infrastructural deficits, and the absence of a coherent policy framework. It therefore recommends the urgent development of a national hydrogen strategy, supported by pilot projects and public-private partnerships, to translate potential into tangible decarbonization outcomes.

DOI: https://doi.org/10.54660/.IJMRGE.2026.7.1.517-522

Keywords: Green Hydrogen, Industrial Decarbonization, Low-Carbon Fuels and Energy Policy

Introduction

As the global community advances toward net-zero targets, governments are increasingly recognizing the role of policies and regulatory frameworks in steering energy transitions (Suleiman *et al*., 2025; Tanko *et al*., 2025) [24]. Beyond conventional renewables like solar and wind, emerging low-carbon technologies, particularly green hydrogen, are gaining momentum as vital tools for industrial decarbonization and heavy transport (Korczak, Kochański, & Skoczkowski, 2022; Sadiq *et al*., 2025) [16,22]. Green hydrogen, produced from renewable-powered electrolysis, has been identified by the International Energy Agency as a "missing piece" in the clean energy puzzle due to its potential to decarbonize hard-to-abate sectors such as steel, cement, chemicals, and long-haul freight (IEA, 2022). Globally, over 40 countries have launched hydrogen strategies, underscoring the technology's centrality in future energy systems (Abdalla, 2024) [1].

Nigeria, as Africa's largest oil and gas producer (Musa *et al*., 2024) [18], faces a dual challenge: balancing its reliance on hydrocarbon revenues with the imperative of decarbonization. The country's industrial sector, heavily dependent on fossil fuels, contributes significantly to carbon emissions and environmental degradation (GGFR, 2022; Adenekan *et al*., 2025) [8,2].

At the same time, Nigeria's Energy Transition Plan (ETP, 2022) identifies green hydrogen and other low-carbon fuels as potential pathways to achieve net-zero emissions by 2060. With abundant renewable resources solar, wind, hydropower, and biomass Nigeria is strategically positioned to develop a green hydrogen economy that could diversify its energy mix, attract foreign investment, and drive industrial competitiveness (REA, 2022).

However, realizing this potential hinge on effective government policies and robust regulatory frameworks. Existing energy policies such as the Renewable Energy Master Plan (2005), the National Renewable Energy and Energy Efficiency Policy (2015), and the Energy Transition Plan (2022) have laid important foundations, but implementation challenges persist, including weak enforcement, inadequate financing mechanisms, and institutional inefficiencies (Onyeji-Nwogu *et al*., 2021; Al-Amin *et al*., 2025). Moreover, fossil fuel subsidies, costing billions annually, undermine the economic case for renewable and low-carbon technologies (IMF, 2022).

This study therefore examines the influence of government policies and regulatory frameworks on Nigeria's adoption of green hydrogen and low-carbon fuels. It also explores their potential to drive industrial decarbonization and shape the country's long-term energy future. By doing so, the research highlights how Nigeria can leverage policy innovation and technological advancement to align national development priorities with global climate commitments.

Statement of the Problem

Nigeria's energy transition is constrained not only by technical limitations but also by the inadequacy of policy frameworks and the neglect of emerging low-carbon energy options. While the country possesses abundant renewable resources and has launched frameworks such as the National Renewable Energy and Energy Efficiency Policy (2015), implementation remains weak, with persistent regulatory uncertainty, overlapping mandates, and poor institutional coordination (Oladipo, 2019; IRENA, 2022). These shortcomings undermine progress toward Sustainable Development Goal 7 (SDG 7) on clean and affordable energy and SDG 13 on climate action (United Nations, 2015) [26].

Emerging low-carbon technologies—particularly green hydrogen—have gained global attention as strategic pathways for decarbonizing heavy industries, transport, and power generation (IEA, 2022). Countries such as South Africa, Morocco, and Egypt are already piloting large-scale hydrogen projects to diversify their energy mix and position themselves competitively in future global hydrogen markets (IRENA, 2022). In contrast, Nigeria has yet to develop a clear hydrogen roadmap, despite its abundant renewable resources that could support cost-effective production. Similarly, opportunities in other low-carbon fuels—such as biofuels and advanced natural gas-based solutions—remain underexplored, leaving a critical gap in Nigeria's decarbonization strategies.

Existing studies on Nigeria's energy transition have focused predominantly on solar and wind technologies (Ohunakin *et al*., 2019; Adewuyi, 2020) [3], with little attention to the techno-economic feasibility of hydrogen and other advanced fuels within the Nigerian context. Furthermore, limited research has examined how governance bottlenecks—such as weak enforcement of existing energy policies, lack of financing mechanisms, and entrenched fossil fuel subsidies—interact with technological gaps to stall innovation (World Bank, 2021) [27]. The neglect of these areas not only slows Nigeria's clean energy progress but also risks locking the country into carbon-intensive development pathways at odds with global net-zero ambitions.

This study seeks to fill these gaps by critically assessing the role of government policies, green hydrogen, and other low-carbon fuels in Nigeria's energy transition. By analyzing policy barriers, technological readiness, and socio-economic implications, it provides a holistic framework for diversifying Nigeria's clean energy portfolio. In doing so, the research advances practical strategies for achieving SDG 7 while positioning Nigeria competitively in the global low-carbon economy.

Conceptual Review

Green Hydrogen and other Low-carbon fuels

Green hydrogen is hydrogen produced through the electrolysis of water using renewable electricity sources such as solar or wind power. Unlike grey hydrogen (produced from natural gas with CO_2 emissions) or blue hydrogen (produced from fossil fuels but with carbon capture), green hydrogen is entirely emissions-free. It can be used as a clean fuel across a wide range of applications (IRENA, 2020). It can replace fossil fuels in industrial high-temperature processes, be used as a feedstock in chemical industries, and power hydrogen fuel cells.

In addition to green hydrogen, other low-carbon fuels such as biofuels, synthetic fuels, and ammonia are gaining attention. These fuels are produced from renewable or sustainable biomass, recycled carbon dioxide, or other carbon-neutral processes. When sustainably sourced and properly managed, these fuels offer pathways for deep decarbonization, particularly in industrial sectors where direct electrification may be technically or economically challenging (IEA, 2021).

The industrial sector is one of the most energy-intensive sectors in Nigeria, accounting for a significant share of the country's greenhouse gas (GHG) emissions. Major industrial activities such as cement production, steel manufacturing, petrochemical processing, and food and beverage production are heavily reliant on fossil fuels, particularly diesel, fuel oil, and natural gas, for both heat and power. As Nigeria pursues a low-carbon development path, decarbonising the industrial sector has become imperative. Among the promising solutions for industrial decarbonization are green hydrogen and other low-carbon fuels, which have the potential to revolutionise energy use in industries while contributing significantly to climate mitigation and sustainable development goals.

Relevance of Green Hydrogen to Nigeria's Industrial Decarbonization

Nigeria has abundant renewable energy resources, including solar, wind, and hydro, which can be harnessed on a large scale to produce green hydrogen. According to the International Renewable Energy Agency (IRENA, 2021), Africa has the potential to become a major exporter of green hydrogen, thanks to its favourable climatic conditions and vast land availability. For Nigeria, investing in green hydrogen offers a dual advantage: it enables decarbonization of the industrial sector while also creating new economic opportunities in a burgeoning global market.

Industries such as cement and steel, which currently rely on carbon-intensive fuels for high-temperature heat, are particularly suitable for hydrogen-based decarbonization. For instance, green hydrogen can replace coal and heavy fuel oil used in cement kilns or serve as a reducing agent in steelmaking, thus drastically cutting emissions. Additionally, green hydrogen can support the development of ammonia-based fertilisers, a critical input for Nigeria's agricultural sector, while reducing the carbon footprint of fertiliser production (Raji, 2025).

Theoretical framework

Energy Transition Theory is a conceptual framework that explores the shift from one dominant energy system to another, often driven by technological advancements, socio-economic pressures, environmental concerns, and policy changes. It was influenced by the work of scholars such as Arie Rip and René Kemp, as well as other researchers involved in socio-technical systems thinking. This theory gained widespread recognition during the global push for cleaner energy following the oil crises of the 1970s and intensified due to increasing awareness of climate change in the 21st century. The theory encompasses not only replacing fossil fuels with renewable sources but also a profound transformation in the production, distribution, and consumption of energy across all sectors (Sovacool, 2016) [23].

At its core, Energy Transition Theory outlines a staged process through which energy systems evolve. These stages typically include pre-development, where alternative energy options are explored; take-off, where interest in new technologies grows and initial policy frameworks are developed; acceleration, marked by large-scale implementation, falling costs, and public acceptance; and finally, stabilization, when renewable energy becomes dominant and the system enters a new regime (Rotmans *et al*., 2001; Cherp *et al*., 2018) [21,5]. Unlike traditional linear development theories, Energy Transition Theory acknowledges the non-linear, multi-actor, and dynamic nature of energy transitions, emphasising the roles of institutions, culture, technology, and governance in shaping outcomes.

Nigeria currently resides in the pre-development to take-off stages, characterised by fragmented but growing policy attention, pilot renewable energy projects, and the foundational work of national frameworks such as the Energy Transition Plan (ETP). However, challenges such as dependence on oil revenues, weak regulatory enforcement, and inadequate energy infrastructure hinder this progression. Energy Transition Theory emphasises the role of governance, financial incentives, and infrastructure planning in overcoming such barriers (IRENA, 2022). Applying this theory helps identify policy gaps, investment opportunities, and strategies for aligning Nigeria's energy transition with global low-carbon pathways.

Empirical Review

Raji (2025) investigates Nigeria's potential to become a leader in Africa's emerging hydrogen economy using a scenario-based mixed-methods approach that integrates stakeholder input with an impact–uncertainty matrix. The study identifies four plausible developmental pathways for Nigeria's hydrogen sector: Hydrogen Leap, Policy-Led Delay, Tech-Driven Push, and Business-as-Usual. Results reveal that while Nigeria has strong comparative advantages—such as abundant natural gas and solar energy resources its progress depends heavily on policy clarity, infrastructure investment, and technological innovation. The study recommends a phased energy transition strategy beginning with blue hydrogen (natural gas with carbon capture), transitioning to green hydrogen as renewable technology becomes more affordable. This study is significant for industrial decarbonization, as it provides a strategic roadmap for balancing short-term economic realities with long-term sustainability goals, demonstrating that hydrogen can diversify Nigeria's industrial base while reducing emissions.

Ajiboye *et al*. (2024) explore the global prospects of green hydrogen as a sustainable alternative to fossil fuels, particularly in the transport and heavy industrial sectors. Using a qualitative analytical framework presented at the SEB4SDG conference, the study emphasizes that green hydrogen is critical to achieving a carbon-neutral economy, but infrastructural costs—especially electrolyzers and storage facilities remain a significant barrier. The authors identify strategic planning, policy formulation, and financial incentives as essential to realizing green hydrogen's potential. They also highlight the role of hydrogen in global trade, suggesting that countries capable of producing cost-efficient green hydrogen will dominate future energy markets. For Nigeria, the study's insights underline the need to invest in technology transfer, capacity building, and research to harness its solar and gas resources for hydrogen production.

This aligns with Nigeria's 2060 net-zero commitment and offers lessons on overcoming technological and policy barriers to industrial decarbonization.

Shari *et al*. (2024) use a bottom-up optimization linear programming model via the Open Energy Modelling Framework (OEMOF) to examine how green hydrogen can enhance electricity access and emissions reduction across five Nigerian Distribution Companies (DisCos). Their findings show that integrating green hydrogen into decentralized electricity generation can lower the levelized cost of electricity by 8%, increase access to electricity, and reduce emissions in the power sector by 2060. The study advocates for a distributed energy generation model that complements Nigeria's Net Zero Transition Plan (NETP). Empirically, this research demonstrates that green hydrogen integration can support localized industrial growth, improve power reliability for manufacturing, and reduce operational carbon footprints directly linking hydrogen deployment to Nigeria's industrial and energy future.

Monye *et al*. (2024) analyze the technical and economic viability of green hydrogen in the Sub-Saharan African context using a comparative evaluation of hydrogen production technologies—electrolysis, thermolysis, photolysis, and biomass conversion. The study identifies economic viability, storage safety, and infrastructural repurposing as major challenges to hydrogen adoption. Their research finds that green hydrogen can play a transformative role in stabilizing power supply, supporting clean industries, and reducing reliance on fossil fuels if policy frameworks reduce investment risks. The authors advocate for government-backed hydrogen value chains, standardization, and investment in research and development to make the hydrogen economy scalable.

Ihugba and Oguzie (2025) provide a macroeconomic and policy-focused analysis of hydrogen's role in Africa's energy transition, emphasizing Nigeria's position as a high-carbon economy with abundant renewable resources. The study situates hydrogen development within Nigeria's Energy Transition Plan (ETP) and the broader African decarbonization agenda. Using comparative data from international hydrogen investments (2021–2022), the study reveals that over 1,700 global hydrogen projects signal growing investor confidence. It highlights Nigeria's potential for solar-driven hydrogen production, given its climatic and resource advantages. The authors recommend comprehensive policy reforms, investment in hydrogen R&D, and public-private collaboration to leverage the hydrogen economy for economic diversification. This study is empirically relevant because it links hydrogen adoption with macroeconomic resilience, showing how Nigeria can mitigate the risks of fossil fuel dependency through hydrogen-led industrial transformation.

Adamu and Sambo (2025) evaluate the economic and policy dimensions of hydrogen as a transition fuel in Nigeria's journey toward 2050 net-zero emissions. Drawing on energy mix data and trend analysis, they argue that hydrogen offers dual benefits: decarbonization and economic diversification amid declining fossil fuel revenues. Their study emphasizes that Nigeria's rich mineral resources, necessary for hydrogen production technologies, present a new revenue pathway as global energy markets evolve. The authors call for strategic investments, institutional reform, and capacity building to position Nigeria as a key hydrogen producer and exporter. The paper establishes hydrogen's potential to reshape Nigeria's industrial landscape, foster green job creation, and enhance the country's global competitiveness in low-carbon technologies.

The reviewed empirical studies collectively demonstrate that hydrogen—particularly green and blue hydrogen holds immense potential for driving Nigeria's industrial decarbonization and sustainable energy transition. They reveal that while Nigeria possesses strong comparative advantages such as abundant solar and natural gas resources, the success of hydrogen deployment depends largely on coherent policy frameworks, infrastructure investment, and technological innovation. Integrating hydrogen into distributed power systems can lower electricity costs, expand energy access, and cut emissions, supporting Nigeria's Net-Zero Energy Transition Plan. Furthermore, developing a hydrogen economy can diversify Nigeria's industrial base, attract foreign investment, and reduce dependence on fossil fuel revenues.

However, realizing these benefits requires overcoming challenges related to high production costs, safety, storage, and the absence of standardized regulations, highlighting the need for coordinated government support, public–private partnerships, and sustained research and innovation.

Methodology

This study employs both qualitative and quantitative approaches to examine Nigeria's transition to renewable energy for decarbonization comprehensively. The rationale for this design stems from the need to capture both numerical trends and contextual insights across technical, policy, and socio-economic dimensions of energy transition (Creswell & Creswell, 2018).

The study focuses particularly on three key geographical zones based on their renewable energy characteristics. Northern Nigeria, comprising states such as Kano, Kaduna, and Sokoto, serves as the focal point for solar energy analysis due to its high solar irradiation levels, averaging 5.5-7.0 kWh/m²/day (ECN, 2022).

A Krejcie & Morgan (1970) [17] table (Appendix C) is used to determine the sample size from the population (N=285 staff in the first six departments). For a 95% confidence level and 5% margin of error, the required sample is 150 respondents, distributed proportionally across departments. To comprehensively address the research objectives, data will be collected through a mixed-methods approach that incorporates both quantitative and qualitative tools, ensuring robust and reliable findings. Primary data collection focuses on gathering firsthand information from the staff of the Energy Commission of Nigeria (ECN) through structured questionnaires, semi-structured interviews, and focus group discussions. Secondary data is obtained from official ECN documents, national energy reports, and international publications to provide contextual background and support primary findings (Creswell & Creswell, 2018) [6].

This section outlines the statistical and analytical techniques to be used in examining both quantitative and qualitative data gathered during the study. For data obtained from the structured questionnaires, descriptive and inferential statistical techniques are applied. The responses are first cleaned and coded using IBM SPSS Statistics (Version 27) to ensure data integrity. Descriptive statistics, including frequencies, percentages, means, and standard deviations, are computed to summarise staff perceptions on renewable energy adoption, policy effectiveness, and institutional barriers (Pallant, 2020).

Data and analysis

This section presents the data collected and analysed using descriptive statistics. The data analysed was collected using the research instrument.

Results

Green hydrogen is emerging as a promising energy carrier for decarbonising Nigeria's industrial and heavy transport sectors. It is recognised globally as a key enabler of net-zero transitions in hard-to-abate sectors such as steel, ammonia, refining, and long-haul logistics. Table 1 presents the opinions on three critical factors: economic viability, renewable energy sufficiency, and the role of international partnerships in enabling hydrogen development.

Table 1: Green Hydrogen Potential in Nigeria

Item	Statement	SD	D	N	A	SA	Total
1.	Green hydrogen is economically viable for Nigeria's industrial decarbonization.	57(38.78%)	42(28.57%)	-	21(14.29%)	27(18.37%)	147(100%)
2.	Nigeria has adequate renewable energy capacity to produce green hydrogen competitively.	44(29.93%)	49(33.33%)	-	30(20.41%)	24(16.33%)	147(100%)
3.	International partnerships are essential for Nigeria's hydrogen development.	15(10.20%)	19(12.93%)	-	52(35.37%)	61(41.50%)	147(100%)

Source: Field survey, 2025.

As revealed in Item 1 of Table 1 on the economic viability of Green Hydrogen, only a minority of 48 respondents (32.66%) agreed that green hydrogen is economically viable for industrial decarbonization in Nigeria. In contrast, 99 respondents (67.35%) expressed disagreement. This substantial doubt reflects the current cost challenges associated with green hydrogen technologies in developing economies, such as Nigeria, where electrolysers, storage systems, and supporting infrastructure remain capital-intensive. Furthermore, high interest rates, inadequate subsidies, and import dependency exacerbate cost-related concerns, making green hydrogen a long-term vision rather than a near-term solution for industrial decarbonization in the country.

Item 2, a similarly cautious view was expressed regarding the sufficiency of Nigeria's renewable energy capacity to support competitive green hydrogen production. A majority of respondents, 93(63.26%), disagreed and strongly disagreed that Nigeria has the necessary generation capacity. At the same time, 54(36.74%) agreed and strongly agreed. These suggest that although Nigeria is rich in solar, wind, and hydro resources, the installed and operational capacity remains far below what is needed for large-scale hydrogen production. Issues such as grid instability, lack of energy storage, and transmission losses further undermine the potential to harness these renewables effectively for electrolytic hydrogen generation.

As revealed in Item 3 of Table 1, unlike the responses to economic and technical viability, respondents overwhelmingly agreed that international partnerships are critical for Nigeria's hydrogen development. A total of 113 respondents (78.87%) strongly agreed or agreed, while 34 respondents (23.13%) disagreed or strongly disagreed, respectively. This implies a growing interest in strategic partnerships and international collaboration to support the development of renewable energy in Nigeria.

Green Hydrogen Economy

Green hydrogen is viewed as a long-term solution for industrial decarbonization, with sectors such as cement, petrochemicals, and steel identified as prime targets for early adoption. A hydrogen innovation expert said:

These industries have high emissions and energy intensity. Green hydrogen can help decarbonise their operations where electrification alone is insufficient.*"*

However, stakeholders cautioned that Nigeria lacks a coordinated hydrogen roadmap. Participants emphasised the importance of learning from countries such as India, Chile, and Morocco, where public-private partnerships and government-backed pilot projects have accelerated early-stage adoption.

Test of Null Hypothesis

H_0: Green hydrogen and other low-carbon fuels do not significantly contribute to the decarbonization of Nigeria's industrial and heavy transport sectors.

A One-Way Analysis of Variance (ANOVA) was also employed to test this hypothesis, as the data satisfied all the assumptions for the analysis. The results of the ANOVA are presented in Table 2.

Table 2: ANOVA Results for Green hydrogen and other low-carbon fuels.

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	P-Value
Between Groups	2.355	5	0.816	1.266	0.026
Within Groups	655.862	915	0.620		
Total	658.217	920			

(F-critical = 1.266, P < 0.05)

From Table 2, the calculated F-value is 1.266, which represents the ratio of variance between the group means to the variance within the groups. The P-value of 0.026 is less than the standard alpha level of 0.05, indicating that the null hypothesis is rejected. Based on these findings, we therefore conclude that Green hydrogen and other low-carbon fuels significantly contribute to the decarbonization of Nigeria's industrial and heavy transport sectors.

Conclusion

This study affirms the significant potential of green hydrogen and other low-carbon fuels to decarbonize Nigeria's industrial and heavy transport sectors, a finding statistically supported by the rejection of the null hypothesis (p-value 0.026 < 0.05). However, the path to realizing this potential is fraught with substantial barriers. Stakeholder perceptions reveal deep-seated concerns regarding the current economic viability of green hydrogen, with a majority (67.35%) doubting its cost-competitiveness, and the adequacy of Nigeria's renewable energy infrastructure (63.26% expressing skepticism). These challenges are compounded by a lack of a coordinated national hydrogen roadmap and the high capital costs of necessary technologies.

Despite these hurdles, there is a strong consensus (78.87%) on the critical role of international partnerships in bridging the technology, financing, and expertise gaps. Therefore, while green hydrogen represents a crucial long-term strategy for aligning Nigeria's industrial growth with its net-zero commitments, its development is contingent upon decisive policy action, strategic investment, and global collaboration to overcome existing economic and infrastructural constraints.

Recommendation

Based on the study's findings, an immediately actionable recommendation is for the Nigerian government to formulate and launch a National Green Hydrogen Strategy and Pilot Program. This initiative should clearly outline phased targets, define regulatory standards, and establish public-private partnerships to co-fund demonstration projects in key industrial zones. By creating a clear policy signal and de-risking initial investments, this approach can mobilize private sector involvement, build local technical capacity, and leverage the international partnerships that stakeholders identified as essential, thereby laying the foundational groundwork for a competitive hydrogen economy without requiring prohibitive upfront national expenditure.

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How to Cite This Article
Aliyu Dahiru Ismaila, Sule Magaji, Ibrahim Musa. Green hydrogen and low-carbon fuels: shaping Nigeria's industrial decarbonization and energy future. Int J Multidiscip Res Growth Eval. 2026;7(1):517-522. doi:10.54660/.IJMRGE.2026.7.1.517-522.