Scenario-Based Planning for Hydrogen Infrastructure and Trade in Nigeria: Navigating Policy, Technology, and Sustainability Uncertainties

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Abstract

The global transition to a low-carbon economy has positioned hydrogen as a critical energy carrier, offering Nigeria—with its abundant natural gas reserves, vast solar potential, and established energy infrastructure—a strategic opportunity to lead Africa's hydrogen economy. This study develops a scenario framework to address uncertainties and opportunities in Nigeria's hydrogen infrastructure and trade, aligning with its Energy Transition Plan and Sustainable Development Goals (SDGs). Through a mixed-methods approach, including stakeholder engagement and literature review, the paper evaluates three hydrogen production pathways: green (renewable-based), blue (natural gas with carbon capture), and grey (conventional gas-based). Each pathway presents distinct trade-offs in cost, emissions, and infrastructure requirements.

The analysis identifies key drivers—technological advancements, policy support, and infrastructure investment—and constructs four plausible scenarios using an impact-uncertainty matrix: Hydrogen Leap (high policy/tech), Policy-Led Delay (high policy/low tech), Tech-Driven Push (low policy/high tech), and Business as Usual (low policy/tech). These scenarios assess Nigeria's potential as a hydrogen exporter to Europe, Asia, and West Africa, considering regional demand, infrastructure readiness, and geopolitical dynamics. A SWOT analysis further highlights Nigeria's strengths (e.g., gas reserves, solar resources) and challenges (e.g., funding gaps, policy ambiguity).

Findings suggest that Nigeria's optimal path involves a phased approach: leveraging blue hydrogen in the short term to capitalize on existing gas infrastructure, while scaling green hydrogen as renewable costs decline. Critical success factors include robust policy frameworks, public-private partnerships, and international collaboration. The study provides actionable recommendations for policymakers and investors, emphasizing the need for targeted incentives, workforce development, and infrastructure modernization. By adopting a strategic roadmap, Nigeria can harness hydrogen to diversify its economy, reduce emissions, and emerge as a key player in the global hydrogen market, ensuring a sustainable and resilient energy future.

Keywords: *Hydrogen economy; Nigeria; Energy transition.*

INTRODUCTION

The global push toward a low-carbon future has positioned hydrogen as a vital enabler of the energy transition. As nations strive to meet net-zero emissions targets, hydrogen is increasingly recognized not only as a clean fuel for domestic use but also as a globally traded energy commodity to achieved energy transition (Agyekum, 2024). It offers substantial potential to decarbonize sectors that are otherwise difficult to abate—such as heavy industry, long-haul transport, and power generation. In response, countries with significant renewable or hydrocarbon resources are mobilizing large-scale investments in hydrogen production, storage, distribution, and export infrastructure.

Hydrogen, the most abundant element on Earth, is not a fuel but an energy carrier with nearly three times the energy content of natural gas, producing clean emissions when used, and must be produced before it can serve as a medium for storing or transporting energy (Amoo & Fagbenle, 2014). Hydrogen, in its various forms, has been used for decades in industries such as chemicals, refining, and manufacturing (Sakthimurugan et al., 2025). Nigeria, with its abundance of natural gas, vast solar resources (Ihugba & Oguzie, 2025b), and established oil and gas infrastructure, is strategically positioned to lead hydrogen development on the African continent. As the continent's largest oil producer (Adeola et al., 2022), Nigeria can leverage its existing energy assets to transition toward a sustainable hydrogen economy. The integration of hydrogen into Nigeria's energy system presents multiple opportunities: decarbonizing domestic energy use, promoting industrial growth, enhancing energy security, and diversifying export revenue streams through participation in emerging hydrogen trade corridors with Europe and Asia. Efforts to decarbonize the Nigerian economy within the framework of the Nigeria Energy Transition Plan must adequately consider the potential for using hydrogen to assist in resolving significant energy issues and achieving decarbonization objectives. Most hydrogen policy blueprints—including those of the EU, IEA, and G7—center around an export-first, techno-centric narrative that prioritizes high-cost green hydrogen production for industrial applications and cross-continental trade. While these models have merit in developed economies, they risk repeating patterns of resource extraction and dependency in the Global South, particularly in countries like Nigeria. Such paradigms often ignore the informal economy, infrastructure asymmetry, and social justice deficits prevalent in Sub-Saharan Africa. Nigeria must not be framed solely as a raw hydrogen exporter to Europe; instead, it must build a contextualized hydrogen model rooted in local resilience, sovereignty, and circular economy logic.

Globally, over 1700 investments in low-carbon hydrogen technologies were made between Q4 2021 and Q4 2022, notwithstanding the challenging economic conditions experienced worldwide (Ihugba & Oguzie, 2025a). An analysis by McKinsey Global Energy Perspective projects a significant growth in the global demand for hydrogen by 2050 - almost sevenfold to 607Mt in an achieved commitments scenario (Nwakaudu et al., 2024a).

Globally, 71% of hydrogen is produced by steam reforming of natural gas as this is the most mature and cheapest way of hydrogen production (Ajanovic et al., 2024a) and Nigeria has an abundance of natural gas (Ani & Ikiensikimama, 2020) . However, the advancement of hydrogen infrastructure and trade in Nigeria remains at an early stage and is hindered by several uncertainties. These include ambiguous regulatory frameworks, underdeveloped physical infrastructure, limited access to financing, market volatility, and the lack of integration of hydrogen into national energy and industrial policies. This paper contributes beyond conventional hydrogen roadmaps in three key ways. First, it applies a localized, trade-oriented perspective that explicitly addresses Nigeria's hydrogen export ambitions, regional demand interdependencies, and physical logistics, including ports and storage. Second, it advances an exploratory, scenario-based foresight framework that incorporates political, technological, and financial uncertainties, offering richer insights than linear forecasts. Third, the study emphasizes multi-stakeholder engagement through expert interviews, ensuring that perspectives from policymakers, financiers, and developers shape the scenario logic. These elements enable the framework to better capture the complexity and volatility of hydrogen development in emerging economies. This approach is grounded in a systemic integration of Nigeria's Energy Transition Plan and the Sustainable Development Goals (SDGs), ensuring that long-term planning is not only economically and technically viable but also socially and environmentally aligned.

Additional complexities arise from the need to choose appropriate technological pathways—such as green, blue, or grey hydrogen—and to evaluate the socio-economic implications of large-scale hydrogen deployment. These uncertainties pose significant challenges for stakeholders, including policymakers, investors, and industry players, in making timely and coordinated decisions.

Despite Nigeria's potential, no comprehensive scenario framework exists to guide hydrogen infrastructure and trade strategies. context-specific scenario framework to support hydrogen infrastructure development and trade strategy formulation. Existing roadmaps tend to be generalized or narrowly focused on production potential, with limited consideration of trade logistics, demand evolution, or stakeholder coordination. To navigate these complexities, scenario planning offers a powerful approach. Unlike linear forecasting methods, scenario frameworks facilitate the exploration of multiple plausible futures (Tavana et al., 2022), this is done by incorporating a diverse range of political, economic, technological, and environmental drivers. This method is particularly relevant to energy transitions, where future developments are nonlinear and shaped by both global influences and local dynamics.

This paper addresses this gap by proposing a scenario-based framework tailored to Nigeria's hydrogen ambitions. The framework aims to identify key uncertainties and emerging opportunities to guide infrastructure development and trade readiness. By doing so, it will support informed, flexible, and resilient policy and investment decisions that are aligned with Nigeria's broader sustainable development and energy transition goals. For so, the paper uses concise reviews of Hydrogen production activities worldwide and interviews.

The findings aim to guide policymakers and investors in navigating infrastructure development, trade opportunities, and SDG alignment (e.g., SDG 7 and 13). By integrating Nigeria's energy transition goals with global hydrogen market trends, this work provides actionable insights for a sustainable hydrogen economy.

Hydrogen production

Hydrogen production is categorized based on the feedstock and production process, leading to green, blue, and grey hydrogen pathways. These scenarios vary in terms of carbon footprint, economic feasibility, technological maturity, and infrastructure requirements. In Nigeria's emerging hydrogen economy, each pathway presents unique opportunities and challenges.

1. Green Hydrogen Scenario (Renewable-Based Production): Green hydrogen is produced via water electrolysis, using electricity from renewable sources such as solar, wind, and hydro. This process generates zero carbon emissions, making it the cleanest hydrogen production pathway.

Key Features

- Feedstock: Water (H_2O)
- Process: Electrolysis (powered by renewable energy)

- Carbon Emissions: 1.0-2.0 kg CO_2/Kg H_2 (N. S. Hassan et al., 2024) depending on the method been used)
- Infrastructure Required: Electrolyzers, renewable energy farms, water desalination (if seawater is used)

Feasibility in Nigeria

- High solar potential: Nigeria receives between 3.5 kWh/m²/day at the coastal areas and 9.0 kWh/m²/day at the northern region of solar radiation (O. Oji et al., 2012), making solar-powered electrolysis viable.
- Hydropower resources: Nigeria has large hydroelectric dams (Kainji, Shiroro, Mambilla), which could support stable power generation for electrolysis.
- Challenges:
  - High electricity cost from renewable sources in early stages (especially concentrated solar and offshore wind), are lower than those for fossil fuel technologies at the lower range of capital costs and discount rates of 10% or lower (Timilsina, 2021). .
  - Water scarcity issues in some regions.
  - Lack of electrolyzer manufacturing capacity in Nigeria.

Use Cases

- Hydrogen exports (to the EU, where green hydrogen demand is rising).
- Fuel for hydrogen-based transportation (e.g., fuel-cell electric vehicles, FCEVs).
- Decarbonization of industrial processes (steel, cement, ammonia production).

Economic and Policy Considerations

- Green hydrogen is currently expensive:~$9/kg H_2 (Q. Hassan et al., 2023) .
- Requires strong government incentives (tax credits, subsidies for renewables).
- Global hydrogen demand may drive future investments.

2. Blue Hydrogen Scenario (Natural Gas with Carbon Capture): Blue hydrogen is produced from natural gas via Steam Methane Reforming (SMR) or Autothermal Reforming (ATR), coupled with Carbon Capture and Storage (CCS) to reduce emissions. This is a transitional hydrogen production pathway for countries with abundant natural gas reserves.

Key Features

- Feedstock: Natural gas (CH_4).
- Process: SMR or ATR with CCS
- Carbon Emissions: can remove 95% of CO_2 with CCS (AlHumaidan et al., 2023)
- Infrastructure Required: Reformers, CCS facilities, natural gas pipelines

Feasibility in Nigeria

- Abundant natural gas reserves over 200 Tcf (Ani & Ikiensikimama, 2020), making low-cost hydrogen production possible.
- Existing gas infrastructure (pipelines, LNG plants) could be repurposed for hydrogen.
- Challenges:
  - High cost of CCS technology in Nigeria.
  - Methane emissions from gas extraction and processing.
  - Limited regulatory framework for carbon capture and utilization (Betiku & Bassey, 2022).

Use Cases

- Hydrogen for industrial processes (fertilizer plants, refineries).

- Hydrogen blending in existing natural gas pipelines.
- Short-term solution for hydrogen exports to global markets.

Economic and Policy Considerations

- Lower cost than green hydrogen ~$1.34/kg H_2 (Hasan & Shabaneh, 2022).
- Requires investment in CCS infrastructure $50–100/ton CO_2 captured considered economically unviable (Hanson et al., 2025)
- Nigeria's National Gas Expansion Program (NGEP) could integrate blue hydrogen in the short term.

3. Grey Hydrogen Scenario (Conventional Natural Gas-Based Production): Grey hydrogen is produced via Steam Methane Reforming (SMR) or Autothermal Reforming (ATR) without carbon capture, making it the most carbon-intensive form of hydrogen production. It currently dominates the global hydrogen market about 95% of production (Anon, 2020).

Key Features

- Feedstock: Natural gas (CH_4)
- Process: SMR or ATR (without CCS)
- Carbon Emissions: High (~9–12 kg CO_2 per kg H_2), 75.6g CO_2/MJ (Howarth & Jacobson, 2021)
- Infrastructure Required: Reformers, gas pipelines

Feasibility in Nigeria

- Cost-effective production ~$1/kg H_2, but high carbon footprint (Hasan & Shabaneh, 2022).
- Uses existing gas infrastructure without additional investment in CCS.
- Challenges:
  - High CO_2 emissions, contradicting global decarbonization goals (Hermesmann & Müller, 2022).
  - Environmental regulations may impose future carbon taxes.
  - Not a long-term sustainable option for Nigeria's energy transition.

Use Cases

- Short-term hydrogen production for refineries and ammonia plants.
- Backup solution until CCS or renewables become widely available.

Economic and Policy Considerations

- Most affordable hydrogen option today.
- Carbon pricing or emissions regulations could increase costs in the future.
- Transition strategy required to shift from grey to blue/green hydrogen.

Key takeaways

- Green hydrogen is the most sustainable but requires high initial investment.
- Blue hydrogen is a viable transition solution, leveraging Nigeria's natural gas resources.
- Grey hydrogen is cost-effective today but faces increasing regulatory risks.

Hydrogen Trade Scenarios for Nigeria: Positioning as a Hydrogen Export Hub

As the global energy transition accelerates, hydrogen is emerging as a critical fuel for decarbonization. Given its vast natural gas reserves, renewable energy potential, and strategic location, Nigeria has the opportunity to become a key player in the global hydrogen market. This analysis assesses potential regional and international trade scenarios to position Nigeria as a hydrogen export hub for West Africa, Europe, and Asia.

1. Regional Market: West Africa's Hydrogen Demand and Trade Potential

The West African region has growing energy needs and seeks to enhance energy security and industrialization. Hydrogen could play a role in power generation, transportation, and fertilizer production with the formulating of ECOWAS green hydrogen policy and strategy framework (ECOWAS, 2023). Nigeria's proximity and energy dominance position it as a key supplier.

Potential Trade Partners

- Ghana, Côte d'Ivoire, and Senegal: Countries investing in industrial hydrogen applications and renewable energy.
- Mauritania and Morocco: North African nations with green hydrogen ambitions that could collaborate on infrastructure development.
- ECOWAS (Economic Community of West African States): Developing regional energy policies that could integrate hydrogen into a broader energy mix.

Export Feasibility and Infrastructure Considerations

- Pipeline Infrastructure: Nigeria can use or expand existing West African Gas Pipeline (WAGP) networks for hydrogen blending.
- Maritime Trade: Hydrogen carriers (ammonia, liquefied hydrogen) could be transported via Lagos and Port Harcourt ports.
- Interconnections with North Africa: Collaboration with Morocco's green hydrogen projects could facilitate hydrogen transit to Europe.

Challenges

- Lack of regional hydrogen policy frameworks in West Africa.
- Need for infrastructure investment in hydrogen transport and storage.
- Uncertain demand growth in local industries.

Table 1: Trade Potential Summary (West Africa)

Factor	Assessment
Market Demand	Moderate (rising energy needs, industrial hydrogen potential)
Infrastructure Readiness	Low (pipelines need upgrades, limited hydrogen-specific investments)
Competitive Advantage	High (Nigeria's dominance in West African energy markets)
Challenges	Policy gaps, funding constraints, industrial adoption uncertainty

2. European Market: Hydrogen Demand and Strategic Trade Opportunities

The European Union (EU) has aggressive hydrogen import targets under its REPowerEU strategy, aiming to reduce reliance on Russian gas and decarbonize heavy industries. Europe seeks green hydrogen from Africa, making Nigeria a strategic partner.

Potential Trade Partners

- Germany: The largest hydrogen consumer in the EU, aiming to import 10 million tons of hydrogen by 2030 (Ansari & Maria Pepe, 2023).
- Netherlands: A major hydrogen transit hub (Rotterdam port) connecting global hydrogen markets to Europe (Breure et al., 2025; der Linde, 2023).
- Spain & Portugal: Key European green hydrogen players, investing in hydrogen pipelines linking Africa and Europe (Urbasos & Escribano, 2024).

Export Feasibility and Infrastructure Considerations

- Maritime Export: Nigeria could export hydrogen derivatives (ammonia, methanol) via deep-water ports.

- Hydrogen Pipelines: Collaboration with North African projects (e.g., Morocco's Xlinks project) could enable pipeline transit (Tanchum et al., 2024).
- LNG Infrastructure Conversion: Nigeria's existing liquefied natural gas (LNG) terminals could be modified for liquid hydrogen exports.

Challenges

- Strict EU regulations on hydrogen emissions: The EU prefers green hydrogen over blue hydrogen (Durakovic et al., 2023).
- Cost competitiveness: Nigeria must scale up renewable energy to produce affordable green hydrogen.
- Infrastructure funding gaps for port expansion and hydrogen shipping.

SWOT Analysis of Nigeria's Hydrogen Market

A SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis provides a strategic assessment of Nigeria's hydrogen market, helping to understand its competitive advantages, challenges, potential growth areas, and external risks.

Strengths (Competitive Advantages)

1. Abundant Natural Gas Reserves for Blue Hydrogen: Nigeria holds the largest natural gas reserves in Africa (~209 TCF), providing a strong foundation for blue hydrogen production using Carbon Capture and Storage (CCS). Established gas processing and export infrastructure (LNG terminals, pipelines) can be repurposed for hydrogen production and trade.
2. High Renewable Energy Potential for Green Hydrogen: Strong solar radiation (~5.5 $kWh/m^2/day$) makes Nigeria well-suited for solar-powered electrolysis. Large hydropower capacity of about 12,000 MW potential (Nchege & Okpalaoka, 2023), providing a stable renewable electricity source for hydrogen production.
3. Strategic Geographic Location for Export: Proximity to European and Asian markets offers a competitive advantage in hydrogen exports. Coastal infrastructure, including deepwater ports (Lagos, Onne, Bonny, Warri), can support hydrogen and ammonia exports.
4. Existing Oil & Gas Expertise and Infrastructure: Nigeria has a well-developed petroleum industry, with a skilled workforce and existing midstream infrastructure (pipelines, refineries, storage facilities) that can be adapted for hydrogen. Companies like NNPC, Shell, TotalEnergies, and Seplat have the technical capability to support hydrogen development.
5. Strong Industrial Demand for Hydrogen: Growing domestic demand from industries such as fertilizer production (ammonia), petrochemicals, and steel manufacturing provides an internal market for hydrogen. Integration of hydrogen with Nigeria's gas-based economy can support decarbonization efforts.
6. Potential for Carbon Capture and Storage (CCS): Nigeria has geologically suitable CO_2 storage sites (depleted oil & gas fields, deep saline aquifers). CCS can reduce CO_2 emissions from hydrogen production by ~90%, making blue hydrogen a low-carbon option. Oil and gas companies (NNPC, Shell, TotalEnergies, ExxonMobil, and Chevron) have experience in subsurface engineering, essential for CCS deployment.

Weaknesses (Limitations and Challenges)

1. Underdeveloped Hydrogen-Specific Infrastructure: Nigeria lacks dedicated hydrogen production, storage, and transport infrastructure e.g., pipelines, refueling stations (Shari et al., 2024). Also Retrofitting existing oil & gas infrastructure for hydrogen usage is capital-intensive and requires significant investments (Harichandan & Kar, 2023).

2. Limited Policy and Regulatory Framework: Absence of a clear national hydrogen strategy leads to uncertainty for investors. Regulatory gaps in hydrogen pricing, safety, and trade policies could hinder market development (Ekpotu et al., 2024; Nwakaudu et al., 2024b; Ojo & Akinmusire, 2023) (Oluwadayomi Akinsooto et al., 2024).
3. High Capital Costs and Financial Constraints: Green hydrogen production via electrolysis is expensive as previously stated. There is limited access to funding and lack of financial incentives make large-scale hydrogen projects in Nigeria (Peter Onuh et al., 2024), thereby making it very challenging.
4. Unstable Electricity Supply: Nigeria's power sector is unreliable, producing ~4,500 MW stable supply with available capacity only 7,141 MW (Adoghe et al., 2023; Ibrahim & Ayomoh, 2022), affecting the viability of green hydrogen production. Frequent grid failures and reliance on diesel generators increase hydrogen production costs.
5. Technical and Workforce Gaps: Limited expertise in hydrogen technologies (e.g., electrolysis, CCS, fuel cells) requires workforce upskilling Research & development (R&D) in hydrogen is underfunded, reducing innovation potential (Ihugba & Oguzie, 2025b; Marvin & Sarkinbaka, 2024; Olajide Henry et al., 2022).
6. Limited CCS Infrastructure and Expertise: Nigeria has no commercial-scale CCS projects (Aminu, 2025; Ogbo et al., 2024), and CCS technology is expensive to develop. These requires High capital costs which includes CO_2 transport, injection, and long-term storage monitoring. There's also Risk of CO_2 leakage and public/environmental concerns over underground storage.
7. Gas Flaring and Methane Emissions: Nigeria flares 2.2 billion cubic feet/day of its natural gas (Nwanya, 2011), contributing to emissions. Methane leaks from gas production, processing, and transport reduce the climate benefits of blue hydrogen. Strict EU regulations on methane emissions may limit blue hydrogen exports.

Opportunities (Growth Potential and Market Expansion)

1. Expanding Hydrogen Exports to Europe and Asia: EU and Asian countries are seeking low-carbon hydrogen imports under Net-Zero targets. Nigeria can leverage EU's €300 billion Global Gateway strategy for hydrogen infrastructure investments (*Global Gateway - European Commission*, n.d.).
2. Carbon Credits and Green Financing: Nigeria can attract green financing from international banks, climate funds (Green Climate Fund, African Development Bank), and carbon offset markets (*Green Climate Fund | African Development Bank Group*, n.d.). Participation in global carbon markets can provide additional revenue streams for blue and green hydrogen.
3. Integration with the African Continental Free Trade Area (AfCFTA): Hydrogen production can support regional energy trade within West Africa. Nigeria can position itself as a hydrogen hub for African industrialization (cement, steel, transportation).
4. Public-Private Partnerships (PPP) for Infrastructure Development: Attracting International Investment & Financing thereby Collaborating with global energy firms (TotalEnergies, Siemens, BP, Shell, Mitsubishi) can accelerate hydrogen infrastructure projects. Leveraging Nigeria's Sovereign Wealth Fund to co-invest in hydrogen projects.
5. Job Creation and Industrial Growth: Hydrogen industry development can create new employment opportunities across the value chain (production, transport, storage, and fuel cells). Hydrogen-based industries (e.g., green steel, ammonia for fertilizers) can diversify Nigeria's economy beyond oil & gas.

6. Decarbonizing the Domestic Economy: Blue hydrogen can help reduce emissions from Nigeria's energy-intensive industries (steel, cement, petrochemicals). Integrating Blue hydrogen with Nigeria's gas-to-power sector can improve electricity reliability while reducing CO_2.
7. Enhancing Gas Utilization and Reducing Flaring: Developing a blue hydrogen industry can provide a profitable alternative to gas flaring, improving Nigeria's environmental performance. Capturing and utilizing associated gas for hydrogen production can increase gas monetization.

Threats (External Risks and Market Barriers)

1. Competition from Established Hydrogen Exporters: North African countries (Morocco, Egypt, Algeria) and Gulf states (Saudi Arabia, UAE) are already advancing hydrogen production and export strategies. Nigeria risks losing global market share if it delays infrastructure development.
2. Policy and Regulatory Uncertainty: Inconsistent energy policies and frequent regulatory changes create uncertainty for investors. Lack of hydrogen-specific incentives may reduce Nigeria's attractiveness as a hydrogen investment destination.
3. Infrastructure Sabotage and Security Risks: Pipeline vandalism, oil theft, and insurgency in the Niger Delta pose threats to hydrogen transportation networks. Political instability and corruption risks may deter foreign investment in large-scale hydrogen projects.
4. Slow Adoption of Hydrogen Technologies: Limited local demand for hydrogen in Nigeria due to dominance of cheaper fossil fuels. High costs of fuel cell vehicles and hydrogen infrastructure could delay domestic market growth.
5. Uncertainty in Carbon Pricing and Global Hydrogen Standards: Variability in global carbon pricing and hydrogen certification standards may affect Nigeria's ability to compete in export markets (Fazeli et al., 2022; van der Ploeg, 2021). Stricter EU regulations on green hydrogen imports could limit Nigeria's export potential if its hydrogen is not deemed low-carbon.

METHODOLOGY

This study employed a qualitative-exploratory research design to develop scenario narratives for Nigeria's emerging hydrogen economy. It utilized semi-structured expert interviews, document reviews, and scenario planning tools, in line with established foresight and energy transition methodologies (Varum & Melo, 2010). To ensure a robust and credible scenario framework for hydrogen infrastructure and trade in Nigeria, key drivers were systematically derived from stakeholder engagement, a total of 17 expert interviews were conducted, including stakeholders from government ministries (Petroleum and environment), private sector hydrogen developers, finance institutions, and academia. Also, questionnaires were distributed to quantify stakeholder perceptions in surveys. Participants were selected using purposive sampling, targeting individuals with strategic, technical, or regulatory insight into Nigeria's energy transition, hydrogen policy, or infrastructure development. The diversity of respondents was crucial to ensure the scenario development captured multiple perspectives.

While the study organized stakeholders into broad categories such as government ministries, private sector developers, finance institutions, and academia, it critically acknowledges significant internal tensions and power asymmetries within these groups. For example, the Energy related parastatals prioritization of hydrogen production in an industrial scale contrast with the Environment Ministry's focus on emissions reduction and sustainable practices. Similarly, within the private sector emphasize large infrastructure investments for export markets while advocating

for decentralized, community-based hydrogen solutions but face capital constraints. Financial actors also diverge between risk-averse commercial banks and development finance institutions prioritizing social impact and long-term sustainability. These nuanced dynamics were systematically coded in the qualitative analysis and have been incorporated into the scenario narratives to reflect the complexity and potential conflict points in Nigeria's hydrogen transition
This sample size meets established benchmarks in qualitative energy policy research. Guest et al., 2006 demonstrated that data saturation—where no new themes emerge—often occurs within the first 12 interviews, especially in expert-driven studies. Vasileiou et al., 2018 confirm that 10–15 interviews are adequate when investigating specialized domains with high-knowledge participants. Bowen, 2008 further supports this range for foresight and scenario planning studies. In this research, convergence in key themes was observed by the 10th interview, with the final few reinforcing and validating the findings. This affirms that thematic saturation was achieved, ensuring the robustness of the scenario framework.

3.2 Data Collection and Analysis: Interviews were conducted virtually and recorded with participant consent. Notes and transcripts were coded using thematic content analysis, guided by the STEEP (Social, Technological, Economic, Environmental, and Political) framework. This helped to identify key impact and uncertainty variables influencing hydrogen deployment in Nigeria. Recurring codes were grouped help in informed scenario framing.

3.4 Emerging Themes and Illustrative Quotes: Several cross-cutting themes emerged, including:

- Infrastructure and investment risk: "No investor will move without clarity on port and pipeline integration."
- Regulatory uncertainty: "We're still waiting on a hydrogen-specific regulatory framework—there's no license yet."
- Technological optimism and skepticism: "Electrolyzer costs will fall, but not fast enough without foreign interest."
- Export ambition vs domestic need: "We want to export green hydrogen, but who's planning for local industrial demand?"

These insights informed the impact-uncertainty matrix and were instrumental in defining the scenario axes.

Stakeholder Influence-Interest Matrix

Table 2: Stakeholder Power/Interest

Stakeholder Group	**Power Level**	**Interest Level**	**Key Internal Divergences / Notes**
Government Ministries	High	High	Energy related Parastatals: export and industrial growth focus; Environment Ministry: climate, emissions, and sustainability focus; coordination gaps between ministries.
Private Sector Developers	High	Medium	Foreign multinational corporations (large-scale, export-driven) vs local SMEs/startups (community-focused, limited capital).
International Agencies	Moderate	High	Technical donors (IRENA, IEA) focused on capacity building vs geopolitical actors (EU, G7) pushing export-oriented green hydrogen.
Finance Institutions	High	Variable	Commercial banks risk-averse, focused on short-term returns; development banks prioritize long-term sustainability and SDG alignment.
Academia & Researchers	Low	High	Division between technocratic/engineering focus and social/environmental justice focus within academia.
Civil Society / Communities	Low	Variable	Often underrepresented, varying acceptance and awareness of hydrogen technologies.

From stakeholder input, drivers were grouped into macro-categories:

Table 3: Macro-Categories

Category	Example Drivers
Technological	Cost of electrolyzers, CCS adoption, local R&D.
Policy & Regulatory	Hydrogen strategy, subsidies, export laws.
Economic & Investment	FDI, public-private partnerships.
Infrastructure	Ports, pipelines, storage facilities.
Market & Demand	Global H_2 prices, domestic offtake agreements.
Socio-Political	Public acceptance, geopolitical risks.

Impact-Uncertainty Matrix

The identified key drivers are ranked based on their impact (significance to hydrogen infrastructure development) and uncertainty (level of unpredictability in their outcomes).

Table 4: Impact-Uncertainty Matrix

Drivers	Impact	Uncertainty
Technological Advancements	High	High
Resource Availability	High	Low
Policy and Regulation	High	High
Infrastructure Investment	High	High
Global Market Demand	High	Medium
Geopolitical and Economic Factors	Medium	Medium

This selection aligns with emerging literature which shows that in nascent hydrogen economies, infrastructure investment is typically driven by enabling policy and cost-reducing technologies rather than acting independently (Ajanovic et al., 2024b; IRENA, 2023). In IRENA's Hydrogen 2023 Outlook emphasized that without strong policy support, infrastructure investments lag, even in high-potential markets. Similarly, McKinsey's global hydrogen projections identify policy and technological advancement as the two largest sources of uncertainty shaping hydrogen deployment outcomes. This prioritization ensures the scenario axes reflect the most impactful and independently uncertain variables.

Key Uncertainties:

1. Technological Advancements (Cost-effective green/blue hydrogen production).
2. Policy and Regulation (Supportive policies, incentives, and enabling frameworks).
3. Infrastructure Investment (Capital investment levels and implementation).

The Impact-Uncertainty Matrix helps in identifying which factors will most shape Nigeria's hydrogen future. Below is the justification for prioritizing Technological Advancements, Policy & Regulation, and Infrastructure Investment (all High Impact, High Uncertainty) for scenario development, while treating others as secondary or contextual factors.

A. High Impact, High Uncertainty (Primary Scenario Axes)

These drivers are most critical because they are both highly influential and unpredictable, making them ideal for scenario exploration.

Table 5: Driver Impact-Uncertainty Justification

Driver	Impact Justification	Uncertainty Justification
Technological Advancements (Cost-effective green/blue H_2 production)	- Determines whether Nigeria can produce hydrogen competitively. - Affects export potential and domestic adoption.	- Rapid innovations in electrolyzers, CCS for blue H_2. - Uncertainty in cost reductions and local adaptability.

Driver	Impact Justification	Uncertainty Justification
Policy & Regulation (Government support, incentives, frameworks)	- Policies dictate investment flows, subsidies, and market creation. - Can accelerate or stall hydrogen projects.	- Political shifts may delay policies. - Unclear if Nigeria will adopt strong H_2 strategies like EU or Middle East.
Infrastructure Investment (Funding for pipelines, ports, storage)	- Without capital, Nigeria cannot build H_2 infrastructure. - Determines scalability of projects.	- Dependent on foreign investment, public-private partnerships. - High risk due to Nigeria's investment climate.

B. High Impact, Lower Uncertainty (Contextual Drivers)
These are important but more predictable, so they are treated as boundary conditions rather than scenario axes.

Table 6: Contextual Drivers

Driver	Why Not a Scenario Axis?
Resource Availability (Solar, gas for green/blue H_2)	- Nigeria has proven solar/gas reserves (low uncertainty). - Impact is high, but availability is not a major unknown.
Global Market Demand (Int'l H_2 trade growth)	- Demand is rising (EU, Asia), but pace is moderately uncertain. - Nigeria's export success depends more on policy & tech than demand itself.
Geopolitical & Economic Factors (Currency stability, int'l relations)	- Medium impact/uncertainty. - Hard to model in scenarios but may be a risk factor.

However, Infrastructure Investment which is a High Impact, High Uncertainty will not be used for Scenario Matrix using these justifications:

- Infrastructure Investment is a Dependent Variable: This is largely driven by policy and technology rather than being an independent uncertainty.
    - Policy & Regulation (e.g., subsidies, tax incentives, public-private partnerships) directly influence investment levels.
    - Technological Advancements (e.g., cheaper electrolyzers, efficient blue hydrogen with CCS) reduce capital costs, making infrastructure more feasible.

  Thus, infrastructure is an outcome of the other two factors rather than a standalone uncertainty.

- Redundancy in Scenario Analysis: including infrastructure investment, may overlap with the other two uncertainties:
    - A scenario with strong policy + advanced tech naturally leads to high investment.
    - A scenario with weak policy + stagnant tech leads to low investment.

  So, removing it simplifies the matrix while still capturing the key drivers.
- Strategic Focus on Root Causes: Policy & Technology are levering that decision-makers can directly influence, whereas infrastructure follows as a consequence. By focusing on these two, actionable insights can be generated (e.g., "How can Nigeria improve policies to attract investment?" or "What technologies should be prioritized?").
- Avoids Overcomplicating the Scenario Space: A 2×2 matrix (High/Low Tech × Strong/Weak Policy) is cleaner and more interpretable than a 3-factor model. It still captures key uncertainties without diluting the analysis.

Therefore, only Technological Advancements and Policy and Regulation will be used to develop plausible scenarios.

Justification for Scenario Dimensions

The scenario framework was constructed using two principal dimensions: policy commitment and technology readiness. These were selected based on their high levels of uncertainty and impact on hydrogen deployment in Nigeria, consistent with established foresight practices.

Policy commitment is highly uncertain in the Nigerian context due to historical inconsistencies in energy policy implementation, regulatory fragmentation, and fluctuating political will. Numerous large-scale energy projects in Nigeria have suffered delays due to unclear policy and regulatory pathways (Ajia, 2025; Nwaiwu, 2021). The International Energy Agency (2022) further emphasizes that in Sub-Saharan Africa, long-term policy certainty is critical to attract hydrogen investment and infrastructure financing.

Technology readiness remains a major constraint. While Nigeria has ambitious hydrogen goals as outlined in the Energy Transition Plan (2022), domestic capacity for electrolyzer deployment, carbon capture integration, and hydrogen storage is still limited. Nigeria lags significantly in renewable energy infrastructure and hydrogen R&D capability compared to global leaders (Ayodele et al., 2021). Hence, the interaction of policy commitment and technology readiness forms the basis for plausible future scenarios that reflect both opportunities and risks.

Scenario Framework Design

Two critical uncertainties, Policy and Regulation and Technological Advancements, are used to create a 2x2 Scenario Matrix:

Table 7: Scenario Matrix

Technological Advancements	High	Low
Policy and Regulation	Scenario 1: Hydrogen Leap	Scenario 2: Policy-Led Delay
Policy and Regulation	Scenario 3: Tech-Driven Push	Scenario 4: Business as Usual

Scenario Narratives

Scenario 1: Hydrogen Leap (High Policy Support + High Technological Advancements)

- The Nigerian government implements robust policies, incentives, and regulatory frameworks to promote hydrogen production.

- Advances in hydrogen technology (using renewables) and cost reductions make production feasible.
- Significant public-private partnerships drive infrastructure investments (production, storage, and export).
- Nigeria emerges as a regional and global hydrogen hub, exporting hydrogen to Europe, Asia, and West Africa.

Features:

- Strong domestic and international markets.
- Job creation, skills development, and economic diversification.
- Environmental benefits through reduced carbon emissions.

Scenario 2: Policy-Led Delay (High Policy Support + Low Technological Advancements)

- Policies and incentives are strong, but technological advancements lag, leading to high production costs for green hydrogen.
- Infrastructure focuses on blue hydrogen production (using natural gas with carbon capture), leveraging Nigeria's natural gas reserves.
- Export opportunities remain limited due to cost barriers and technological inefficiencies.

Features:

- Gradual infrastructure development.
- Moderate economic and environmental benefits.
- Long-term reliance on natural gas.

Scenario 3: Tech-Driven Push (Low Policy Support + High Technological Advancements)

- Technological breakthroughs drive down the cost of hydrogen production (green and blue), but policy and regulatory frameworks remain weak.
- Investments are led by private sector actors and international partners targeting export markets.
- Domestic adoption remains limited due to lack of government support and enabling infrastructure.

Features:

- Export-oriented hydrogen production.
- Limited domestic benefits for energy transition.
- Slow infrastructure growth due to regulatory gaps.

Scenario 4: Business as Usual (Low Policy Support + Low Technological Advancements)

- Weak policy support and slow technological advancements prevent significant hydrogen development.
- Nigeria continues to rely on traditional energy sources (oil and gas), missing global hydrogen opportunities.
- Infrastructure investments remain stagnant, and international competitiveness declines.

Features:

- Low economic growth and diversification.
- Missed opportunities for environmental and energy transition goals.
- Continued reliance on fossil fuels.

Scenario Evaluation and Comparison

The scenarios will be analyzed and compared based on key performance indicators (KPIs) to assess their feasibility and impacts:

- Economic Feasibility: Total cost of infrastructure investments, profitability, and return on investment (ROI).
- Environmental Impact: Carbon emission reductions under each hydrogen production pathway (green, blue, or grey hydrogen).
- Market Readiness: Nigeria's competitiveness in hydrogen export markets.
- Policy and Regulatory Gaps: Identifying areas where policy interventions are required to achieve a desirable scenario.

Table 8: Scenario Comparison

Criteria	Scenario 1: Hydrogen Leap	Scenario 2: Policy-Led Delay	Scenario 3: Tech-Driven Push	Scenario 4: Business as Usual
Economic Feasibility	High (low costs, strong ROI)	Moderate (higher costs)	Moderate (export-focused)	Low (no investments)
Environmental Impact	High (renewables-driven)	Moderate (natural gas-based)	High (global markets benefit)	Low (fossil fuel reliance)
Market Readiness	High (domestic and export)	Low (slow market adoption)	High (export-oriented)	Low (no readiness)
Policy & Regulatory Gaps	Minimal	Strong policies but slow tech	Weak policies, strong tech	Significant gaps

Hydrogen Workforce Capacity Map & Skills Gap Analysis

Despite Nigeria's extensive oil and gas expertise, significant workforce gaps exist in key hydrogen technologies such as electrolyzer operation, CCS, pipeline integrity for hydrogen transport, and fuel cell maintenance.

Table 9: Current Workforce Status

Sector	Existing Skills	Gaps Identified
Oil & Gas (midstream)	Strong	Lacks H_2 safety and pipeline retrofitting
Renewable Energy	Growing	Weak in electrolyzer installation and integration
Chemical Engineering	Moderate	Needs retraining for ammonia and methanol from H_2
Power Sector	Weak	Inadequate for fuel cell systems and grid-H_2 integration

Table 10: Oil and Gas to Hydrogen Skills Gap

Oil/Gas Role	**H_2 Equivalent Role**	**Skill Gaps**	**Training Modules Required (Duration)**
Pipeline Technician	H_2 Transport Specialist	H_2 embrittlement knowledge	H_2 Materials Safety (80 hrs)
Process Engineer	Electrolysis Plant Ops	Water treatment systems	PEM Electrolyzer Operations (120 hrs)
Gas Plant Operator	CCS Facility Technician	CO_2 capture monitoring	Amine Scrubbing Systems (60 hrs)
Petroleum Geologist	Subsurface H_2 Storage	H_2-rock interactions	Geologic H_2 Storage (100 hrs)

Workforce Development Recommendations

1. Development of National Hydrogen Skills Development Center (NHSDC) under the Energy Commission of Nigeria (ECN) to coordinate industry-academia upskilling.
2. Hydrogen Certificate Programs in engineering schools or tertiary institutions.
3. Train-the-Trainer schemes with support from International Energy Companies.

International Hydrogen Trade and Cooperation

To position Nigeria as a strategic hydrogen exporter, a corridor initiative with Niger, Morocco, and the EU is proposed. This corridor would align infrastructure, regulations, and trade policies to facilitate hydrogen transport to Europe.

Key Components:

- Pipeline Interoperability: Standardizing pressure ratings and hydrogen blending limits.
- Tariff Harmonization: Streamlining cross-border customs to reduce project delays.
- Logistics Coordination: Shared terminals, hydrogen hubs, and financing mechanisms.
- Regulatory Alignment: Harmonizing safety, quality standards, and carbon accounting frameworks.

Current barriers include EU methane leakage regulations, differing pipeline materials, and weak transnational agreements. The H_2-NIMEC Corridor envisions a North–South hydrogen export axis with harmonized trade policies, infrastructure interoperability, and joint investment.

Proposed Route:Nigeria → Niger → Algeria/Morocco → Spain/Europe via H_2 pipelines or ammonia tankers.

Table 11: Harmonization Goals

Policy Domain	Harmonization Focus	Recommendation
Tariffs	Avoid double taxation of H_2 or derivatives	Adopt ECOWAS and AfCFTA-based trade exemptions
Transport Logistics	Common safety, inspection & refueling protocols	Joint corridor certification and permitting authority
Pipeline Standards	Material integrity, H_2 blending limits	Cross-border pipeline code adoption via UNECE Hydrogen Safety Group
Customs & Export Licensing	Simplified processes	Establish "green lane" for H_2 exports within ECOWAS
Environmental Standards	Emission certifications	Joint green H_2 certification registry with EU compliance
Investment Guarantees	Risk-sharing frameworks	African Hydrogen Fund with EU–AfDB support for corridor investments

Key Contributions Beyond Conventional Roadmaps

This work contributes to the growing body of hydrogen transition studies by introducing three major enhancements over traditional roadmap methodologies:

- Localized and Trade-Oriented Perspective: While most hydrogen plans are generalized at national or global levels, this study focuses on Nigeria's unique geopolitical and energy landscape, especially its strategic potential to become a hydrogen export hub for Europe. This regional focus provides contextually relevant insights often overlooked in top-down roadmaps.
- Exploratory Scenario Framework: Conventional roadmaps typically rely on deterministic trajectories. In contrast, this paper employs an impact-uncertainty matrix to develop four contrasting scenarios. This enables stakeholders to consider multiple plausible futures and assess strategy robustness across them.
- Systemic SDG and Policy Integration: The scenarios are explicitly linked to Nigeria's Energy Transition Plan (ETP) and the United Nations Sustainable Development Goals (SDGs). This systemic alignment supports multi-sectoral engagement, guiding not only technology development but also inclusive policy formulation.

Advancing Beyond Existing Hydrogen Roadmaps

This framework advances beyond existing national and international hydrogen strategies in several important ways. Table 2 summarizes the comparative strengths of this scenario-based approach.

Table 12: Comparative strengths of this scenario-based approach

Dimension	Existing Roadmaps (IEA, AU, NNPC)	This Framework
Geographic Focus	Global or national (mostly developed countries)	Nigeria-specific with regional trade lens
Scenario Approach	Deterministic pathways	Exploratory, multi-scenario foresight

Dimension	**Existing Roadmaps (IEA, AU, NNPC)**	**This Framework**
Scenario Diversity	Limited (e.g., low/medium/high tech)	Four diverse futures capturing complexity
Policy-SDG Alignment	Often treated separately	Integrated with Nigeria's ETP and SDGs
Stakeholder Engagement (Implied)	Top-down (expert/policymaker-led)	Tri-sector framing (policy, tech, private)
Trade Dynamics	Assumes fixed global supply-demand structure	Explicit focus on West Africa-EU corridor

By embedding uncertainty, SDG alignment, and regional trade positioning into a structured foresight approach, this study provides a policy-relevant and context-specific tool for guiding Nigeria's hydrogen transition. It allows stakeholders to stress-test strategies under multiple futures and highlights the institutional and technological gaps that must be addressed to avoid a hydrogen lockout.

In contrast to existing hydrogen plans or framework (ECOWAS, 2023; H2 Diplo, 2023) that narrowly focus on production capacity or cost competitiveness though Nigeria has not officially developed its National Hydrogen Policy as it is still a work in progress (H2 Diplo, 2025), this work holistically integrates trade-readiness, infrastructure bottlenecks, and stakeholder roles. By simulating futures along the axes of policy/regulatory dynamics and technology adoption pathways, the resulting scenarios provide grounded foresight for a hydrogen-exporting nation like Nigeria. The stakeholder-informed design adds legitimacy and utility to the scenarios, making them actionable for government strategy and investor risk planning.

Conclusion

Nigeria's hydrogen future should follow a phased approach, starting with blue hydrogen due to its cost-effectiveness and leveraging natural gas resources. In the long run, green hydrogen will become dominant as renewable energy costs decrease. Policymakers must implement strategic incentives, infrastructure investments, and regulatory frameworks to transition towards a low-carbon hydrogen economy.

Through scenario evaluation, it is evident that Scenario 1 (Hydrogen Leap) presents the best economic, environmental, and market opportunities for Nigeria. Achieving this will require robust policy support, technological advancements, and strategic infrastructure investments. By addressing policy and regulatory gaps and capitalizing on Nigeria's energy potential, the country can position itself as a leading player in the global hydrogen market.

Recommendations Based on Scenario Analysis

1. Prioritize Policy and Regulatory Frameworks:
    - Develop strong incentives, supportive policies, and clear regulatory guidelines for hydrogen production, storage, and export.
2. Leverage Technological Innovations:
    - Invest in R&D for green hydrogen technologies and collaborate with international partners to adopt cost-effective solutions.

3. Infrastructure Investment Strategies:
    - Promote public-private partnerships to fund hydrogen infrastructure, ensuring a balance between domestic and export market readiness.
4. Global Market Integration:
    - Position Nigeria as a key hydrogen supplier for Europe, Asia, and West Africa to maximize economic and trade opportunities.
5. Workforce Development:
    - Develop training programs to upskill and reskill the workforce for the hydrogen economy, ensuring alignment with Nigeria's energy transition goals.

Strategic Roadmap for Nigeria's Hydrogen Development

1. Short-Term (0–5 years): Focus on Blue Hydrogen
    - Leverage natural gas reserves to produce blue hydrogen with CCS.
    - Develop pilot projects in industries (refineries, ammonia production).
    - Integrate hydrogen blending into natural gas pipelines.
    - Develop a National Hydrogen Strategy and regulatory framework.
    - Establish pilot blue and green hydrogen projects in collaboration with private investors.
    - Improve power sector stability to support large-scale electrolysis.
2. Medium-Term (5–10 years): Expand Renewable Hydrogen
    - Scale up solar and hydropower investments to power electrolysis.
    - Establish hydrogen export agreements with the EU and Asia.
    - Develop hydrogen storage and transport infrastructure.
    - Scale up hydrogen production infrastructure (pipelines, storage, refueling stations).
    - Integrate hydrogen into Nigeria's domestic energy mix (power generation, industrial use).
3. Long-Term (10–20 years): Achieve Green Hydrogen Dominance
    - Transition from blue to green hydrogen as renewable energy costs decline.
    - Implement nationwide hydrogen mobility solutions (fuel cell vehicles, hydrogen refueling stations).
    - Establish a hydrogen economy framework with strong policy support.
    - Position Nigeria as a global hydrogen export leader.
    - Develop a regional hydrogen hub for West Africa, supplying ECOWAS countries.

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