NIGERIA4H2

A critical analysis of the Potentials, infrastructure and other enabling framework conditions for Green Hydrogen-to-fertiliser production in Nigeria

WASCAL
West African
Science Service Centre on
Climate Change
and Adapted Land Use

With funding from the :

Federal Ministry
of Research, Technology
and Space

Citation: WASCAL (2025), *A critical analysis of the Potentials, infrastructure and other enabling framework conditions for Green Hydrogen-to-fertiliser production in Nigeria*, West African Science Service Centre on Climate Change and Adapted Land Use, Accra, Ghana.

ABOUT WASCAL

The West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) is a West African intergovernmental organization, headquartered in Accra, Ghana, with a current membership of 12 countries: Benin, Burkina Faso, Cabo Verde, Cote d'Ivoire, The Gambia, Ghana, Guinea, Mali, Niger, Nigeria, Senegal and Togo.

WASCAL provides comprehensive climate change solutions, through capacity building, research and innovation, climate and environmental services, as well as the promotion of green hydrogen and renewable energy. **www.wascal. org**

Acknowledgements

This report was developed under the guidance of Dr. Bruno Korgo (Renewable Energy and Green Hydrogen Coordinator, WASCAL), with valuable input and comments from WASCAL experts: Dr. Kouakou Valentin Koffi, Mr. Julien Bulgo, Dr. Prosper Kokou Semekonawo, Dr. Bagaya Noufou, Mr. Sam Firmin, and Mr. Victorien D. Ouedraogo.

The publication and editorial process was led by Mr. Marc Belemsobgo, with support from Mr. Igor Bado. The report is based on research conducted by DECHEMA e.V., (consultant) in collaboration with a consortium of Nigerian partners comprising the Federal University of Technology, Akure; Afe Babalola University; the Federal University of Technology, Minna; and Cognity Advisory

WASCAL acknowledges the generous funding provided by the German Federal Ministry of Research, Technology and Space (BMFTR).

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ABBREVIATION	MEANING
ACE-FUELSA1:B101	African Centre of Excellence in Future Energies and Electrochemical Systems
AfDB	African Development Bank
AKK	Ajaokuta-Kaduna-Kano
APP	Agricultural Promotion Policy
ASTM	American Society for Testing and Materials
ASU	Air Separation Unit
ATA	Agricultural Transformation Agenda
AWE	Alkaline Water Electrolysis
BMFTR	Federal Ministry of Research, Technology and Space (Germany)
BOOT	Build-Own-Operate-Transfer
CAPEX	Capital Expenditure
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
DAP	Diammonium Phosphate
DECHEMA	Society for Chemical Engineering and Biotechnology (Germany)
ECN	Energy Commission of Nigeria
ECOWAS	Economic Community of West African States
EIA	Environmental Impact Assessment
ELPS	Escravos-Lagos Pipeline System
EPC	Engineering, Procurement, and Construction
FAO	Food and Agriculture Organization
FGN	Federal Government of Nigeria
FMIST	Federal Ministry of Innovation, Science and Technology
FMP	Federal Ministry of Power
FMWR	Federal Ministry of Water Resources
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GHG	Greenhouse Gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GPHI	Global Programme for Hydrogen in Industry
GW	Gigawatt
GWh	Gigawatt hour
H_2	Hydrogen
H_2Diplo	Hydrogen Diplomacy
HRI	Hydrogen Research Institute
INDC	Intended Nationally Determined Contribution
IPP	Independent Power Producer
IRENA	International Renewable Energy Agency
IWRM	Integrated Water Resources Management
$kWh/m^2/day$	Kilowatt-hours per square meter per day
LCBC	Lake Chad Basin Commission
LCOH	Levelized Cost of Hydrogen
LNG	Liquefied Natural Gas

LPG	Liquefied Petroleum Gas
MJ/kg	Megajoule per kilogram
MMSCFD	Million Standard Cubic Feet per Day
Mt	Million Tonnes
MW	Megawatt
MWh	Megawatt hour
NACHRED	National Centre for Hydropower Research and Development
NASPA-CCN	National Adaptation Strategy and Plan of Action on Climate Change for Nigeria
NATIP	National Agricultural Technology and Innovation Policy
NBA	Niger Basin Authority
NCCC	National Council on Climate Change
NCEE	National Centre for Energy & Environment
NCEEC	National Centre for Energy Efficiency and Conservation
NCERD	National Centre for Energy Research and Development
NCPRD	National Centre for Petroleum Research and Development
NDC	Nationally Determined Contribution
NERC	Nigerian Electricity Regulatory Commission
NERMC	National Energy Reserve Management Company
NESI	Nigerian Electricity Supply Industry
NESREA	National Environmental Standards and Regulations Enforcement Agency
NETP	Nigeria's Climate Change Act and the Nigeria Energy Transition Plan
NGC	Nigerian Gas Company
NGFCP	Nigerian Gas Flare Commercialisation Programme
NIHSA	Nigeria Hydrological Services Agency
NIMASA	Nigerian Maritime Administration and Safety Agency
NIWA	National Inland Waterways Authority
NLNG	Nigeria Liquefied Natural Gas Limited
NMDPRA	Nigerian Midstream and Downstream Petroleum Regulatory Authority
NMGP	Nigeria-Morocco Gas Pipeline
NNEL	NNPC New Energy Limited
NNPC	Nigerian National Petroleum Corporation
NPA	Nigerian Ports Authority
NPK	Nitrogen, Phosphorus, Potassium
NPSC	Nigerian Pipelines & Storage Company
NRCL	NNPC RefChem Limited
NREAP	Nigeria Renewable Energy Action Plan
NREEEP	National Renewable Energy and Energy Efficiency Policy
NSC	Nigerian Shippers' Council
NSL	NNPC Shipping Limited
NUPRC	Nigerian Upstream Petroleum Regulatory Commission
OPEX	Operating Expenditure

LIST OF ABBREVIATIONS

PEM	Proton Exchange Membrane
PIA	Petroleum Industry Act
PMS	petroleum modified spirit
PPP	Public-Private Partnership
PV	Photovoltaic
PWC	PricewaterhouseCoopers
RE	Renewable Energy
REA	Rural Electrification Agency
RIPLE	Renewables Investment Platform for Limitless Energy
SERC	Sokoto Energy Research Centre
SMR	Steam Methane Reforming
TCF	Trillion Cubic Feet
TJ	Terajoule
UNIDO	United Nations Industrial Development Organisation
UPW	Ultrapure Water
WASCAL	West African Science Service Centre on Climate Change and Adapted Land Use
WHO	World Health Organisation

EXECUTIVE SUMMARY

Context and Rationale

Nigeria possesses immense potential to become a regional leader in green hydrogen and green ammonia production, leveraging its abundant renewable and conventional energy resources to drive sustainable economic growth and agricultural transformation. The "NIGERIA4H2" study, initiated by WASCAL with support from the Federal Republic of Germany, provides a critical assessment of the technical, infrastructural, policy, and investment conditions necessary for establishing a robust green hydrogen-to-fertiliser value chain in Nigeria.

Although Nigeria is Africa's largest economy and most populous nation, it continues to face persistent energy deficits, with only 61.19% of the population having access to electricity in 2023 (Energy Progress Report 2025). The agricultural sector, contributing nearly 30% of GDP and employing over one-third of the workforce, is hindered by limited mechanisation and inadequate access to key inputs. Fertiliser supply remains insufficient: despite surplus urea production, Nigeria relies on imports for other key types such as NPK.

Green hydrogen, produced from Nigeria's vast renewable energy resources—solar, hydropower, wind, and biomass—offers a transformative opportunity to address these challenges. When synthesized into green ammonia, hydrogen offers a sustainable, domestically sourced input for fertiliser production, thereby improving the reliability of fertiliser supply chains and contributing to enhanced national food security. This aligns with Nigeria's broader policy objectives for economic diversification, energy transition, and climate resilience.

Key Findings

- **Energy Resource Endowment**

Nigeria is endowed with diverse renewable energy resources capable of supporting large-scale green hydrogen and green ammonia production. The country's solar photovoltaic (PV) potential is estimated at 210 GW, with global horizontal irradiance ranging between 3.5–7.0 kWh/m²/day and up to 2,200 kWh/m²/year in northern states such as Sokoto and Katsina. Nigeria's hydropower potential exceeds 14,250 MW, though only about 2,850 MW is currently installed. The wind energy potential is estimated at 3.2 GW, particularly in northern and coastal regions, where average wind speeds range from 5 to 7 m/s. Biomass resources are also abundant, with 144 million tons available annually, complemented by agricultural and forest residues, animal waste, and municipal solid waste. The country possesses vast water resources, including both surface and underground sources, to support electrolysis. In regions such as Borno State, the maximum technical hydrogen production from groundwater reaches up to 40.00 kWh/(yr·m²), with several other zones averaging around 20.00 kWh/(yr·m²). Overall, based on land availability and renewable resource density, Nigeria holds a theoretical potential to produce over 16,000 TWh of green hydrogen per year, placing it among the most promising nations for green hydrogen production globally.

- **Policy and Regulatory Framework**

Nigeria has taken steps to promote renewable energy and industrial development through policies such as the Renewable Energy Master Plan and the National Energy Policy. However, specific frameworks and incentives for green hydrogen and ammonia are still required to unlock investment and position the country in the global low-carbon economy. Relevant water-related policies include the National Water Resources Act (1993), the National Water Policy (2016), and the Water Resources Master Plan (2013), which prioritise domestic and agricultural water use, establish licensing systems for industrial water withdrawal, and emphasise integrated water resource management (IWRM). Additionally, the National Agricultural Technology and Innovation Policy (NATIP) aims to incentivise local fertiliser production and reduce gas dependency. At the regional level, the ECOWAS Green Hydrogen Policy provides a guiding framework for Nigeria. It outlines harmonised regulations, shared infrastructure strategies, and regional trade mechanisms for hydrogen and its derivatives. Nigeria is encouraged to align with this policy and use it as a blueprint to develop its national green hydrogen roadmap, encompassing fiscal incentives, safety standards, land-use planning, water resource management, capacity building, and research initiatives. Accelerated policy development, regulatory clarity, and targeted support are urgently needed to attract investment, stimulate innovation, and build domestic expertise in the sector.

- **Stakeholders**

The successful development of hydrogen and particularly green hydrogen in Nigeria requires active engagement and coordination across a wide array of stakeholders. These include six key categories of actors: (1) ministries and regulatory authorities, (2) banks and investors, (3) international partners and donors, (4) active industrial players, (5) technical service providers, and (6) academic and capacity-building institutions. Among state actors, the Federal Ministry of Power, the Ministry of Environment, the Ministry of Agriculture, and the Ministry of Water Resources and Sanitation—together with agencies like NERC, NESREA, NIHSA, the Rural Electrification Agency (REA), and the National Council on Climate Change will play central roles. The National Water Resources Institute and the network of River Basin Development Authorities are particularly critical for regulating and monitoring water access and allocation for hydrogen projects. Given the multisectoral nature of green hydrogen, stronger interministerial coordination is urgently required, especially for balancing water demands across energy, agriculture, and domestic sectors. A national cross-sectoral platform or inter-agency task force should be established to align planning and policies, ensure regulatory coherence, and facilitate stakeholder dialogue. The private sector including local and international energy developers, fertiliser companies, EPC contractors, and logistics providers will also be instrumental in project implementation. Development finance institutions, commercial banks, venture capital, and multilateral agencies (such as ECOWAS, GIZ, UNIDO, and AfDB) are vital for de-risking investments. Research institutions and training centres including WASCAL will play a key role in ensuring local workforce readiness, technology absorption, and innovation.

- **Infrastructure and Technology**

While Nigeria has a substantial installed power generation capacity, actual available power is less than half, and grid reliability remains low. Water resources for electrolysis are available but require targeted investments in infrastructure and management. Nigeria's existing renewable energy infrastructure comprising over 2 GW of large hydropower capacity (e.g., Kainji, Jebba, Shiroro), several solar farms like the 10 MW Kano plant, and small-scale wind installations, though modest, provides a foundational platform for scaling up green hydrogen production via electrolysis. While the country currently lacks dedicated hydrogen production facilities, its extensive LPG/LNG infrastructure, including the 22 MTPA Bonny Island LNG terminal and more than 390,000 MT of LPG storage capacity, presents a strategic opportunity for repurposing and accelerating the development of a domestic green hydrogen industry. This convergence of renewable assets and gas infrastructure offers a critical springboard for the large-scale deployment of green hydrogen technologies in Nigeria. Regarding hydrogen transport, Nigeria's 1,990 km natural gas pipeline network, including the AKK Pipeline, could be adapted for hydrogen transport. Ports such as Lagos and Onne already support LNG exports and could be used for green hydrogen derivatives like ammonia. Nigeria also participates in the Nigeria–Morocco pipeline initiative, which could facilitate hydrogen exports to Europe. Ongoing infrastructure projects include solar and wind installations, green hydrogen pilot plants, and partnerships to retrofit existing ammonia facilities (e.g., Dangote, Indorama, Notore)

- **Potential Cost of Green Ammonia Produced in Nigeria**

As part of the assessment of Nigeria's green hydrogen potential, three production scenarios were developed to estimate the scale of green ammonia output for fertiliser use and export. These scenarios reflect varying levels of ambition, infrastructure investment, and policy direction, each with specific implications for domestic fertiliser supply and the country's role in the global green ammonia market.

In the Local NPK Scenario, the focus is on substituting imported ammonia-based fertiliser precursors specifically DAP and GAS with domestically produced green ammonia. Green ammonia is assumed to be produced in newly built facilities, while existing urea plants continue operating with natural gas. Under this scenario, green ammonia production is relatively modest, growing from approximately 13,000 tonnes in 2030 to 357,000 tonnes annually by 2060. This represents about 8% of projected total ammonia demand, requiring approximately 63,000 tonnes of green hydrogen per year by 2060.

The Best Guess Scenario envisions a more ambitious pathway, combining increased domestic fertiliser supply with large-scale production for export. Green ammonia output rises to over 3.17 million tonnes per year by 2060, accounting for 50% of projected total ammonia demand. This level of production would require about 562,000 tonnes of green hydrogen annually. The scenario assumes the construction of dedicated green ammonia facilities operating alongside Nigeria's existing gas-based plants.

The most expansive, the H_2 Diplo Scenario, targets Nigeria's emergence as a global green ammonia exporter. Under this scenario, green ammonia production ramps up rapidly after 2030, reaching approximately 4.75 million tonnes per year by 2060 equivalent to 60% of total ammonia demand. Meeting this output would require over 843,000 tonnes of green hydrogen annually. This scenario assumes substantial investment in new infrastructure and is aligned with global low-carbon market trends.

- **Socioeconomic and Environmental Impact**

Expanding green hydrogen and ammonia production can generate significant economic, social, and environmental benefits. It positions Nigeria to become a continental leader in the green hydrogen sector, fostering technology transfer, industrial growth, and regional trade. Green hydrogen will help diversify Nigeria's economy beyond oil and gas, while supporting rural development and job creation. Environmentally, green ammonia offers a low-carbon alternative to fossil-based fertilisers and aligns with Nigeria's 2060 net-zero target. It reduces GHG emissions, supports the National Climate Change Policy, and contributes to cleaner air, water, and soil. By replacing fossil-fuel-based urea, green ammonia has the potential to lower emissions in Nigeria's agricultural sector, one of the country's highest-emitting sectors.

- **Challenges**

Nigeria faces several key challenges in advancing its green hydrogen and ammonia production ambitions. Persistent energy supply deficits and unreliable grid infrastructure pose significant barriers to scaling up electrolysis, which depends on stable and abundant electricity. Additionally, gaps in water infrastructure and resource management make it challenging to ensure the large volumes of purified water required for electrolysis are consistently available. The lack of dedicated policy and regulatory frameworks for green hydrogen and ammonia further undermines investor confidence and hampers coordinated sector development. Moreover, the high upfront capital costs associated with renewable energy systems, electrolyser technology, and ammonia synthesis facilities demand robust public-private partnerships to mobilise financing. Finally, there are notable capacity constraints across research, technology adoption, and workforce development, limiting the pace and depth of innovation and local value chain integration.

- **Opportunities**

Nigeria's abundant renewable energy resources present a significant opportunity to establish the country as a regional hub for green hydrogen and ammonia production. By capitalising on its vast solar, hydropower, and wind potential, Nigeria can reduce its dependence on imported fertilisers, thereby strengthening national food security and agricultural resilience. The development of a green hydrogen economy also promises to create new jobs and stimulate the growth of value chains. Additionally, these emerging sectors are likely to attract international investment and facilitate technology transfer, accelerating Nigeria's industrial and technological advancement. Importantly, expanding green hydrogen and ammonia production aligns closely with Nigeria's broader climate and energy transition goals, contributing to emissions reduction commitments while fostering sustainable economic growth.

- **Recommendations**

To successfully unlock Nigeria's green hydrogen and ammonia potential, a comprehensive and coordinated approach is essential. The following recommendations aim to guide policymakers, investors, and stakeholders in building a sustainable and competitive green hydrogen economy:

- Develop a National Green Hydrogen Strategy by establishing clear targets, incentives, and regulatory frameworks to guide public and private investment in green hydrogen and ammonia.
- Invest in Renewable Energy and Water Infrastructure, prioritizing projects that ensure a large-scale, reliable supply of clean electricity and water for electrolysis.
- Foster Public-Private Partnerships to leverage international expertise and financing, accelerating technology transfer and local capacity building.
- Promote Local Value Chains by supporting domestic manufacturing of electrolysers, fuel cells, and fertiliser production facilities to maximize economic benefits.
- Enhance Stakeholder Engagement through inclusive dialogue among government, industry, academia, and civil society to align green hydrogen development with national priorities.
- Integrate Green Hydrogen into Agricultural Policy by positioning green ammonia as a core component of Nigeria's fertiliser strategy to boost productivity and sustainability.
- Strengthen Policy and Regulatory Frameworks to provide clarity and stability, attracting long-term investment and fostering innovation in the green hydrogen sector.

Green hydrogen presents Nigeria with a strategic opportunity to drive sustainable energy development, catalyze industrial transformation, and enhance agricultural resilience. By fully harnessing its abundant renewable resources and investing in robust enabling frameworks, such as clear policies, regulatory stability, and targeted infrastructure, Nigeria can accelerate the emergence of a competitive green ammonia industry. Moreover, fostering inclusive public-private partnerships and engaging diverse stakeholders will be critical to unlocking innovation, mobilizing capital, and building local capacity.

Ultimately the development of a first green ammonia pilot plant could serve as a demonstration and learning hub, paving the way for broader adoption and scale-up across Nigeria and the wider West African region. To achieve this, the study recommends establishing a strategic partnership anchored around one of the country's existing ammonia plants with the active support of the government, as well as international financial and technical partners.

INTRODUCTION

Since the Paris agreement in 2015, Green Hydrogen has gained significant momentum due to its large potential to decarbonise industrial and energy sectors. Although there is considerable potential for hydrogen production to surpass global demand, current policies and infrastructure advancements are lagging behind this potential [1]. This gap is mainly attributable to the slow pace of hydrogen infrastructure development, the high costs associated with producing low-emission hydrogen, and insufficient policy support [2]. Effective policy support must ensure hydrogen investments while prioritising applications where hydrogen is essential [1]. According to International Energy Agency (IEA) analysis, the cost of producing hydrogen from renewable electricity could decrease by 30% by 2030, driven by falling renewable energy costs and increased hydrogen production scale. Additionally, mass manufacturing is expected to reduce costs for fuel cells, refuelling infrastructure, and electrolysers [3].

In alignment with its climate commitment, Nigeria has set ambitious targets under its Nationally Determined Contribution (NDC) to address climate change and accelerate the transition to a low-carbon economy. Nigeria's updated NDC commits to reducing greenhouse gas emissions by 20% unconditionally and up to 47% conditionally by 2030, relative to business-as-usual projections. Achieving these targets requires significant investments in renewable energy, energy efficiency, and sustainable industrial development, including the adoption of innovative solutions such as green hydrogen. By integrating green hydrogen into its decarbonization strategy, Nigeria aims to diversify its energy mix, reduce reliance on fossil fuels, and support the development of climate-resilient sectors such as agriculture and manufacturing. These commitments underscore the strategic importance of advancing green hydrogen infrastructure and policy as part of Nigeria's broader efforts to meet its climate goals and foster sustainable economic growth [4].

As of January 2025, Nigeria holds proven oil reserves of 37.5 billion barrels and gas reserves of 209.26 trillion cubic feet (TCF), according to the Nigerian Upstream Petroleum Regulatory Commission [5]. These substantial reserves position the country as a major player in Africa's energy sector. Beyond these conventional resources, the country has significant renewable energy potential: an estimated hydropower capacity of 14,120 MW, average solar irradiation ranging from 3.5 to 7.0 kWh/m²/day, wind resources estimated at 150,000 TJ/year, and about 144 million tonnes of biomass annually [6-8].

Despite these assets, Nigeria faces chronic energy deficits. Of its installed generation capacity of 16,384 MW, only around 7,140 MW are actually available, with distributed power rarely exceeding 4,000 MW [10]. As a result, 59.5% of the population had access to electricity in 2021, with rural electrification falling as low as 26.35% [11]. Most rural and peri-urban communities remain off-grid and rely heavily on traditional biomass, with adverse impacts on public health and the environment.

This energy situation directly affects the agricultural sector, which accounts for 29.94% of GDP and employs over 36% of the labour force [11, 12]. Mechanisation remains limited, and shortages of key inputs, particularly fertilisers, constrain productivity and threaten food security. Although national fertiliser production is growing, it remains insufficient to meet consumption, creating a supply gap that leaves the country vulnerable to fluctuations in global markets.

Further, the Nigerian fertiliser market is characterised by high demand but constrained supply, leading to significant reliance on imports. This dependency exposes the sector to price volatility and supply chain disruptions, affecting agricultural productivity and food security. Efforts to localise fertiliser production, including exploring green ammonia-based fertilisers, are critical to enhancing the resilience and sustainability of Nigeria's agricultural inputs market.

To address these challenges, the Nigerian government is promoting economic diversification and sustainable development, encouraging commercial agriculture and renewable energy deployment through instruments like the Renewable Energy Master Plan (Energy Commission of Nigeria, updated version) and the National Energy Policy. Within this framework, green hydrogen is emerging as a transformative solution. Produced from renewable energy, it can be converted into green ammonia, a key component for fertiliser production. This would reduce import dependence, lower carbon emissions, and support sustainable agricultural growth [14].

In this context, WASCAL, supported by the Federal Republic of Germany through the Federal Ministry of Research, Technology and Space (BMFTR), has initiated the "NIGERIA4H2: A Critical Analysis of the Potentials, Infrastructure and Other Enabling Framework Conditions for Green Hydrogen-to-Fertiliser Production in Nigeria" project. The implementation of this project is driven by a strong collaboration between WASCAL, Local institutions such as the Federal University of Technology Akure (FUTA), the Federal University of Technology Minna (FUTMina), the Afe Babalola University, and Cognity Advisory.

The project aims to provide an in-depth assessment of Nigeria's green hydrogen potential and the necessary conditions for its industrial deployment, with a particular focus on green fertiliser production. The study reviews existing infrastructure, current policies, technological and investment needs, and offers actionable recommendations to guide a just energy transition tailored to local realities. Built on extensive stakeholder consultation, it provides decision-support tools to strengthen dialogue between the Nigerian government and potential partners or investors, paving the way for sustainable green hydrogen exploitation as a clean energy source and driver of agricultural development.

The report first provides an overview of Nigeria's energy sector, highlighting the nation's vast conventional and renewable energy resources, current generation capacity, and patterns of energy use. It then explores the technical fundamentals and global context of green hydrogen, including production pathways, value chains, and emerging international opportunities. The analysis continues with a detailed assessment of Nigeria's infrastructure covering power generation and transmission, water resources, and industrial assets relevant to hydrogen and ammonia production. The policy, regulatory, and investment landscape is then examined, identifying existing frameworks, gaps, and opportunities for accelerating green hydrogen adoption.

Building on this foundation, the report presents scenario-based projections for green ammonia production and fertiliser demand, alongside an evaluation of economic, social, and environmental impacts. Further sections discuss technological options, financing mechanisms, and stakeholder engagement strategies essential for successful project implementation. The document concludes with a synthesis of key findings and practical recommendations, setting the stage for Nigeria's transition to a sustainable green hydrogen and fertiliser economy.

1. NIGERIA ENERGY SECTOR

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1.1. Energy Potential

Nigeria, with a landmass of about 917,434 km², is a country endowed with an abundant array of energy resources, both conventional and renewable, which, if well harnessed, would not only ensure energy security (full, nationwide electrification) but could also propel significant economic development. From its vast oil and gas reserves to its promising renewable energy sources, each federating State in Nigeria has the potential energy resources to develop its economy to full capacity (Figure 1).

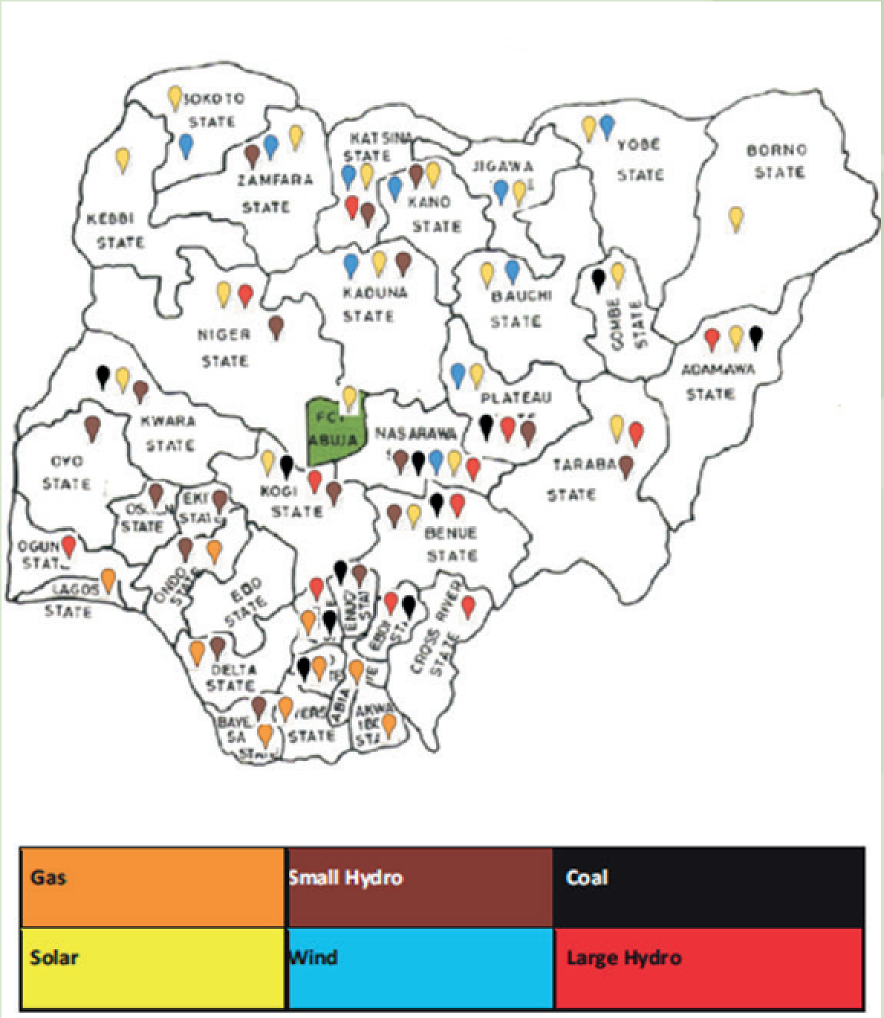

Figure 1: Nigeria energy resources distribution map [14]

According to the Nigerian Upstream Petroleum Regulatory Commission (NUPRC), Nigeria's proven reserves in 2024 included 37.50 billion barrels of crude oil and condensate, and 209.26 trillion cubic feet (TCF) of associated and non-associated gas [5]. Within these totals, crude oil accounted for 31.56 billion barrels and condensate for 5.94 billion barrels. The reserves of associated gas and non-associated gas totalled 102.59 trillion cubic feet (TCF) and 106.67 TCF, respectively.

With these reserves, the country ranks 10th globally in terms of total oil reserves and 8th in terms of gas reserves. However, a US Geological Survey estimates that the gas reserves potential in Nigeria could be as high as 600 trillion cubic feet [17]. Nigeria also has large rivers and natural waterfalls that could be used to generate hydropower, with a potential estimated at over 14,120 MW[18].

Renewable energy resources in Nigeria

The development of renewable energy is crucial to reduce Nigeria's dependence on fossil fuels, meet the growing energy demand (particularly in many off-grid locations) and unlock the green hydrogen potential. In this light, the Nigeria Renewable Energy Master Plan set ambitious targets to increase renewable energy's share in its energy mix to 10% by 2025, 20% by 2030, and 35% by 2050 (Table 1).

Target	2025	2030	2050
Solar	5,700 MW	11,800 MW	47,600 MW
Hydro	2,600 MW	5,300 MW	14,500 MW
Wind	400 MW	800 MW	2,500 MW
Biomass	200 MW	400 MW	1,300 MW
Total	8,900 MW	18,300 MW	65,900 MW
Percentage of total energy mix	10%	20%	35%

Table 1: Policy targets for Nigeria's renewable energy [19]

In achieving these targets, some sector specific developments are being pursued and are highlighted in the section below.

- **Solar Energy**

Nigeria has a vast solar potential, with an average daily solar annual global horizontal irradiation ranging between 1,600 kilowatt hours per square metre (kWh/m2) and 2,200 kWh/m2, particularly in the Northern regions of Sokoto, Katsina, and Kano states. The solar photovoltaic (PV) potential is put at 210 gigawatts (GW), when only 1% of the suitable land is utilised for project development, while the potential for concentrated solar power (CSP) is approximated to about 88.7 GW [13,18]. Nigeria has an average of 4–7 peak sun hours per day, depending on the region, with estimated solar radiation ranging between 3.5–7.0 kWh/m2/-day, thus favouring solar energy development (Figure 2).

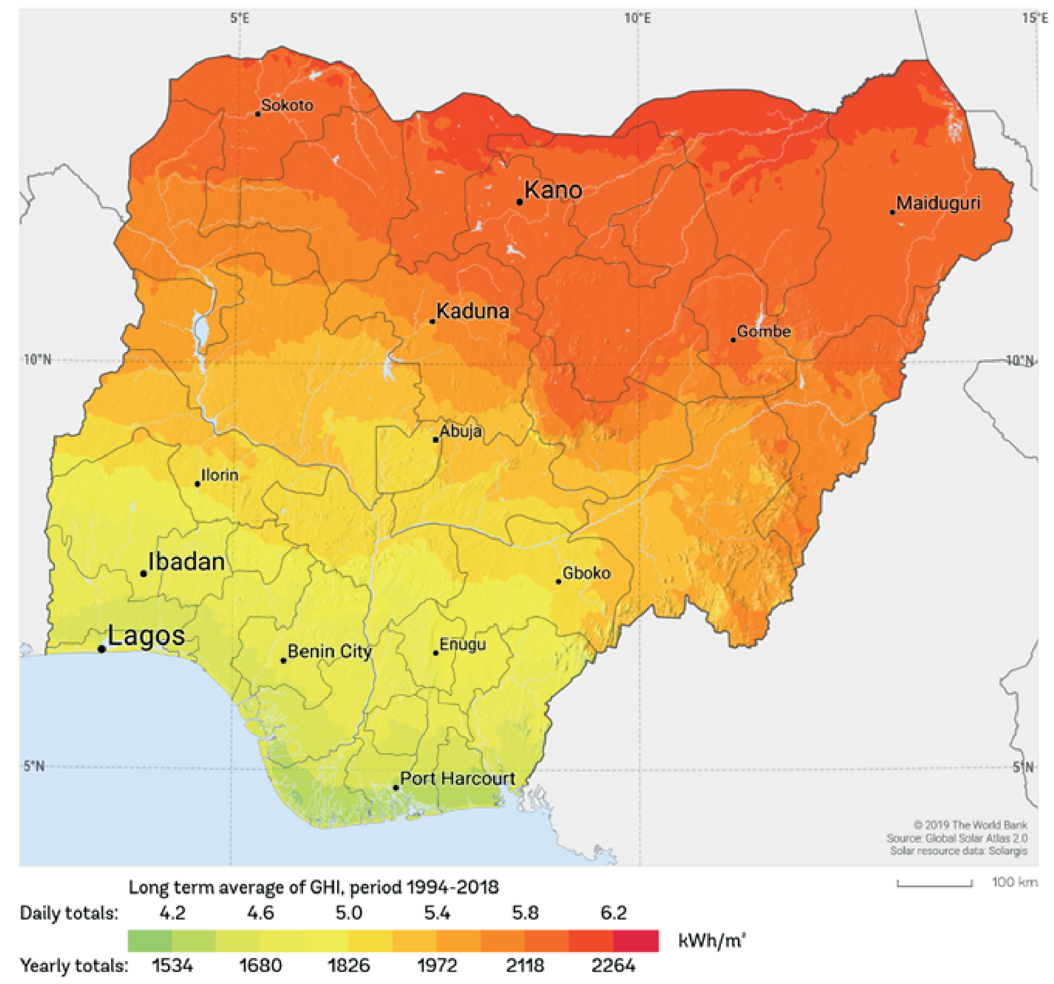

Figure 2: Average solar radiation distribution over Nigeria [19]

Despite its significant potential, solar energy utilization in Nigeria remains largely limited to household-scale applications. A few mini-grid installations exist, with capacities reported at 28 MW in 2019 and 28.3 MW in 2021, according to the Solar Report of Nigeria (2021) and the Rural Electrification Agency (REA) report of January 2023. The notable solar mini-grid projects in Nigeria include:

- o The 5MW Ariaria Market Solar Project to power the popular Ariaria Market.
- o The 30MW Kaduna Solar Power Plant to supply electricity to the national grid and was developed by DLO Energy Group.
- o The 10 MW Kano Solar Plant, which aims to reduce energy shortages in the Kano metropolis, was inaugurated in Kano State in early 2023.
- o The 30MW Sokoto Solar Power Plant is aimed at supplementing energy to the Sokoto metropolis. The plant was develop by SkipperSeil Limited.
- o The 17MW Ogun Solar Project, developed by W Energy Limited, to power some utilities in an industrial estate.
- o The 10MW Enugu Solar Project, constructed by NESCO Engineering to boosts energy supply in Enugu State.
- o The 20MW Niger Delta Solar Project, developed by New Energy Services Company, to promotes renewable energy in the Niger Delta region.

- o The 12MW Lagos Solar Project, built by CPCS Transcom Limited, to complement power genera tion in Lagos.
- o The 15MW Abuja Solar Project, developed by Aitel Limited, to complement power generation in the Federal Capital Territory, and
- o The 10MW Yola Solar Project, financed by the Adamawa State Government, to promotes renewable energy in Yola.

The gap between potential and installed capacity is staggering, with Nigeria having only tapped into about 6.81% of its solar potential. Grid-connected solar accounts for 60% (19 MW) of the installed capacity, while off-grid solar accounts for 40% (10 MW). This situation underscores the need for increased investment in solar energy infrastructure. This presents significant opportunities for large-scale solar development, off-grid solar solutions, and rooftop solar installations. If grid-connected utility solar PV is to reach the 2030 target gradually, the estimated generation capacity should be 2.6 GW, 2.9 GW, 3.2 GW, 3.5 GW and 3.8 GW between 2023 and 2026. Realistically, mini-grid installation in Nigeria lagged behind the set targets. However, there are proposals to install 961 MWp across various states (Abuja, Kogi, Edo, Gombe, and Nasarawa) with a 443 MWh of utility-scale Battery Energy Storage System. This solar PV off-grid initiative aims to expand energy access to unserved and underserved rural communities. Through the efforts of Nigeria's Rural Electrification Agency (REA) in establishing additional mini-grid projects in line with the NREAP (2015–2030), the installed capacity is projected to increase from 300 MW in 2022 to 700 MW by 2026 [6]. Notable recent projects include the 990 kW interconnected mini-grid in Lambata, Niger State; the 550 kWp solar hybrid mini-grid in Plateau State; and the 440 kWp interconnected mini-grid in Cross River State. These projects were implemented under the Interconnected Mini-Grid Acceleration Scheme (IMAS), supported by a €9.3 million in-kind grant funded by the European Union and backed by the German Cooperation [20]. Also, the 8.25MW, 2.5MW, 1.12 MW and 1.35 MW Solar Hybrid Captive Power Plant were commissioned at the Federal University of Agriculture Makurdi, Nigerian Defence Academy (NDA) Kaduna, Abubakar Tafawa Balewa University, Bauchi and the Federal University of Petroleum, Effurun respectively under the Energising Education Programme (EEP). The EEP with an estimated total capacity of 89.6MW is expected to power 37 Federal Universities and 7 Teaching Hospitals in Nigeria [23].

Other proposed mini-grid solar developments, according to the Rural Electrification Agency, include:

- o The 1.2 GW Oando Group Solar Project, with the first phase, a 600 MW solar power rollout scheduled for completion in 2026. The project is in partnership between Oando Clean Energy and the Rural Electrification Agency.
- o The 1 GW Jigawa Solar PV, which is to be financed by the African Development Bank, is aimed at electrifying 100 villages in Jigawa State [24].
- o The 100 MW Gombe State Solar Energy Plant. The project is a partnership between China Railway 18th Bureau Group and Gombe State to develop to boost local energy self-sufficiency [25].

- Gombe Solar PV Park - The 270MW Solar PV project (Gombe) is expected to be commissioned by 2026. The project financed by Niger Delta Power Holding is developed by Sun Africa; Sterling and Wilson [26].
- The 360MW Gezhouba- Lagos Solar PV Park. The project is a partnership between Falcore Power and Energy Limited and China Gezhouba Group Company Limited. The project is expected to be commissioned in 2026.
- The 5,600MW Argungu Solar PV Park project (Kebbi) - The project is a partnership between the Kebbi State Government and South-Africa based investor, Equity Electricity Company. The project is expected to enter commercial operation in 2027.

To underscore Nigeria's commitment to the development of the solar energy potential, the country enacted policy initiatives to stimulate local manufacture of components required in the solar energy value chain, including the modules. For instance, the imposition of a 10 per cent tariff on imported panels boosts the business case for local production. A number of local photovoltaic assembly firms, such as Auxano Energy, are currently in operation [25]

- **Hydropower Energy**

Nigeria has a substantial hydro potential, with numerous rivers and streams that can be harnessed for clean power generation and also support green hydrogen development. The country's hydro potential is estimated to be around 14,250 MW, which is largely untapped. The most suitable areas for hydroelectric power development are the northern and central regions, where the Niger and Benue rivers flow. The country had an installed hydropower capacity of approximately 2850 MW boosted by the recently energised 40 MW Kashimbila (Taraba State) hydropower plant, commissioned in 2019, and the 40 MW Dadin Kowa (Gombe State) hydropower plant, commissioned in 2020, 700 MW Zungeru (Niger State) hydro power plant commissioned in 2023. Five small-scale hydropower plants within the mix are 30 MW Gurara 1 (Niger State), 10 MW Tiga and 8 MW Challawa (Kano State), 10 MW Oyan (Ogun State), and 6 MW Ikere (Osun State) [28].

Coincidentally, most of the hydroelectric power plants are located in parts of Nigeria with vast land and relatively high average solar radiation; thus, it may be helpful to explore green hydrogen production downstream.

- **Wind Energy**

Nigeria has substantial wind potential, particularly in the northern and coastal regions, with average wind speeds ranging from 5-7 m/s. The windiest areas include the northeastern states of Borno, Yobe, and Jigawa, as well as coastal areas like Lagos, Ogun, and Oyo (Figure 7). With an estimated wind potential of 3.2 GW, Nigeria has vast opportunities for wind farm development, hybrid power systems, and off-grid electrification [20]. Despite this potential, there is no notable wind farm projects currently operational. The main challenges hindering wind energy development in Nigeria include poor datasets on wind speed and wind profiles, technical and institutional capacity gaps, and limited access to financing. Addressing these challenges and leveraging opportunities would help in boosting renewable energy capacity. Decentralized energy access through off-grid wind solutions can create jobs, stimulate economic growth, reduce greenhouse gas emissions, and improve energy security and diversification.

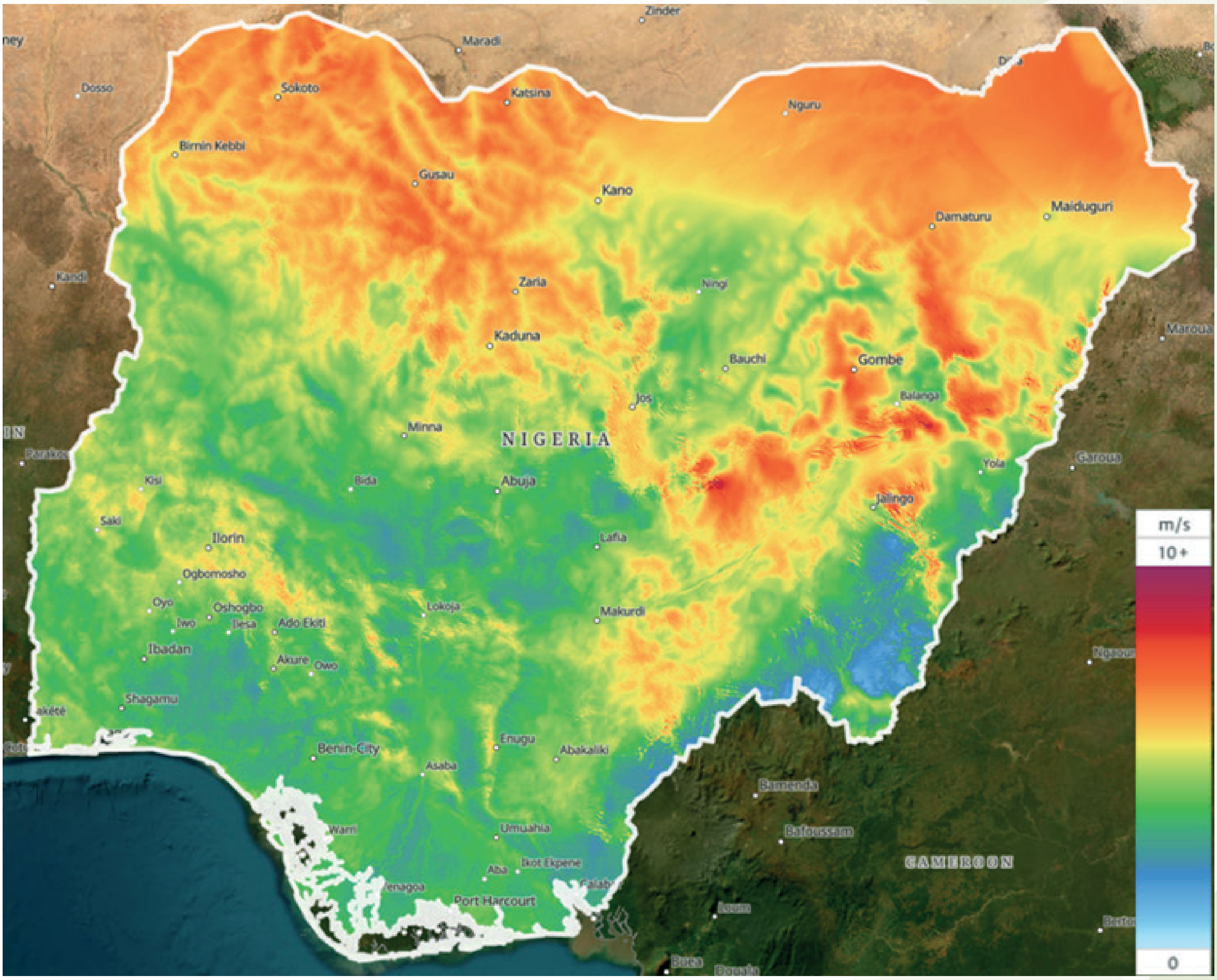

Figure 7: Nigeria wind map[27]

- **Bioenergy**

Nigeria possesses significant bioenergy potential due to its diverse biomass resources, including agricultural and forest residues, animal and human wastes, and municipal solid waste (MSW). The country has approximately 21 million hectares (Mha) of forest cover, generating substantial residues from logging and wood processing activities. Agricultural land spans about 69 Mha, with residues alone capable of producing an estimated 697.15 terajoules (1.09 EJ) of energy [28]. Animal wastes contribute roughly 0.65 EJ annually, while human wastes provide around 0.03 EJ per year. Additionally, municipal solid waste from urban centres contains a substantial organic fraction suitable for energy recovery through processes such as anaerobic digestion or incineration. Despite the identified potential and existing policies, not much has been done in the implementation of large-scale bioenergy within Nigeria, and sustainable management of these residues tranches is crucial to prevent deforestation and environmental degradation currently associated with bioenergy [31]. As at today, major bioenergy projects are being proposed in Nigeria including the Jigawa Ethanol plant, Niger State Ethanol plant and Dangote Ethanol plant etc. Traditional bioenergy plays a large role in the energy sector of Nigeria, meeting nearly half of final energy consumption in recent times, although more effective and climate-smart usage is proposed [32]. Nigeria aims to increase the contribution of renewable energy to 10% of total energy consumption by 2025, emphasizing the development of bioenergy among other renewable sources [33]. Based on the policy target for Nigeria renewable energy, Nigeria planned to harness it biomass potential with a target of 200MW in 2025, 400MW in 2030 and 1300MW in 2050 [19].

In summary, Nigeria remains abundant in renewable and non-renewable energy resources in West Africa. By 2025, Nigeria's energy sector will have an installed capacity of 13,625 MW, with effective production ranging between 4,500 MW and 5,800 MW. The energy mix is still dominated by natural gas, which accounts for over 70% of electricity generation. However, renewable energies are gradually taking a back seat in the national strategy, with investments noted. Solar power installation with off-grid mini-grids in rural areas by 2021 is 28.5 MW, and several utility projects under development are expected to generate around 100 MW. The country has a potential of 14250 MW, of which the installed capacity is 2850 MW, representing 20% of national production. Also, numerous projects are underway. Despite the country's 69 million hectares of forest, bioenergy is still marginal. However, a few biogas projects have been set up in rural areas. The wind power sector is also very limited at present, but a potential of around 10 GW is available. Once these projects are up and running, Nigeria will be able to reach the 30 % share of renewable energies in the electricity mix by 2030, according to its energy master plan.

1.2. Energy Mix and Future Plan

In Nigeria, traditional biomass and waste remain the dominant sources of energy for domestic cooking and heating. Crude oil accounts for a comparable share of the country’s primary energy consumption, while natural gas, hydropower, and other renewable sources constitute the remainder, primarily serving the power sector for electricity generation (IRENA, 2023). This suggest that while the primary energy supply for Nigeria has a very substantial non-fossil share, its composition has negative externalities. In terms of electricity, Nigeria has a total installed power generation capacity of 16,384 MW, mainly from large hydro dams and fossil fuel (gas) fired thermal power plants. The hydro power plants provide 2,062 MW while gas-fired power plant supplies 11,972 MW. Solar, wind, and other sources such as diesel and Heavy Fuel Oil (HFO) constitute the remainder with 2,350 MW (Nigerian Energy Report, 2019; USAID, 2021). A small portion of Nigeria's electricity mix is coal-based (less than 1%), although there are plans to generate about 7700MW from coal in the near future (Table 1). The prevalence of traditional biomass in the primary energy mix and the widespread use of natural gas-fired plants for electricity generation are key drivers of Nigeria’s carbon emissions.

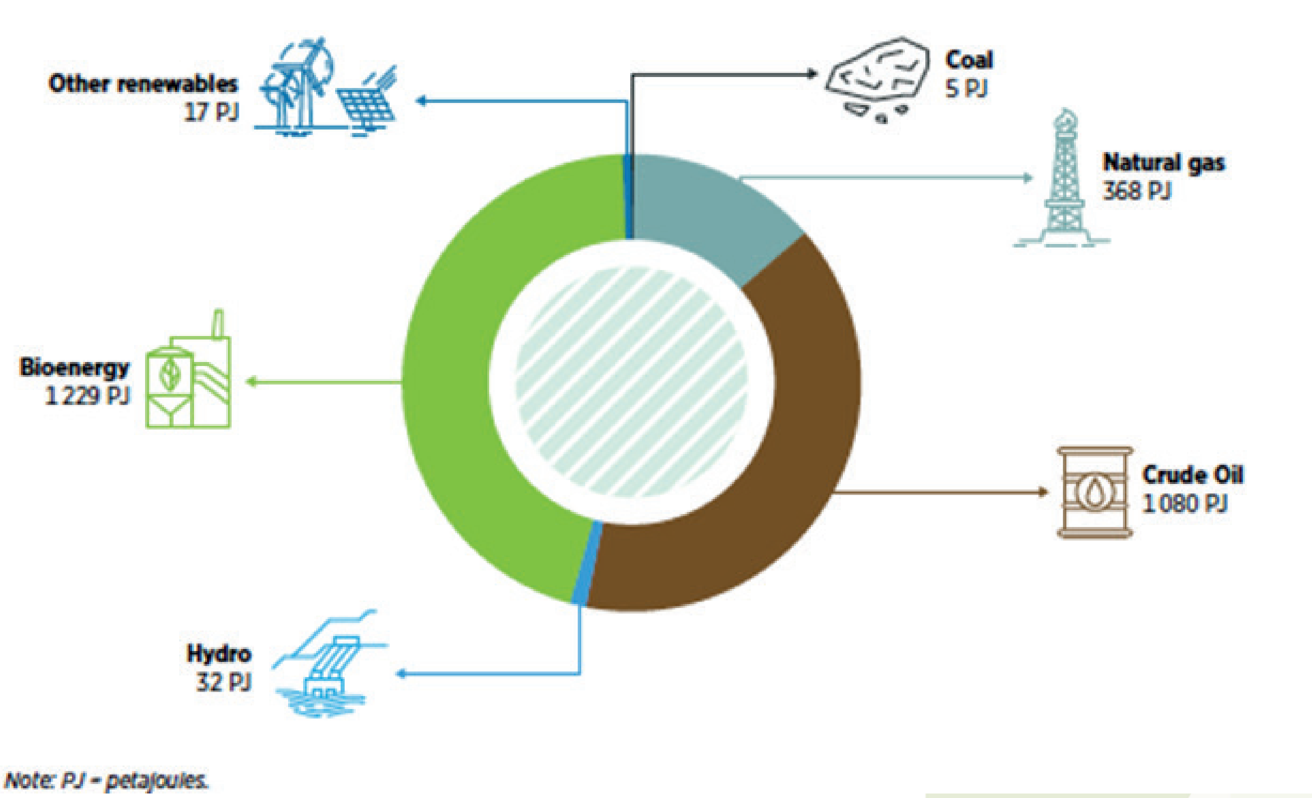

Figure 4: Nigerian primary energy supply in 2015 base year [30]]

As shown in Table 2, in 2024, Nigeria has 12 operational power plants with a total installed capacity of about 4500MW (2700MW from 4 Large Hydro Dam and 1800MW from gas-fired plants). In addition, 14 partially operating gas-fired plants have a combined installed capacity of about 8700MW, while gas-fired plants with a capacity of about 2500MW are either non-operational or stalled in the construction phase [25, 26].

	Power Plants	Owner	Type	Location	Commissioned	Capacity (MW)	Status
1	Kainji Power Station	FGN	Hydro	Niger State	1968	760	Operational
2	Jebba Power Station	FGN	Hydro	Niger State	1984	540	Operational
3	Shiroro Power Station	FGN	Hydro	Niger State	1990	600	Operational
4	Trans-Amadi	IPP	Gas	Rivers State	2004	136	Operational
5	Okpai/Kwale-Okpai	IPP	Gas	Delta State	2005	480	Operational
6	Omoku I	NIPP	Gas	Rivers State	2005	150	Operational
7	Aba Power Station	IPP	Gas	Abia State	2012	140	Operational
8	Zamfara Power Station	FGN	Hydro	Zamfara State	2012	100	Operational
9	Gbarain	NIPP	Gas	Bayelsa State	2017	225	Operational
10	Azura Power Station	IPP	Gas	Edo State	2018	450	Operational
11	Rivers IPP-A	IPP	Gas	Rivers State	2025	180	Operational
12	Zungeru	NIPP	Hydro	Niger State	2023	700	Operational
13	Tiga	Kano State	Hydro	Kano State	2024	10	Operational
14	Itobe	IPP	Coal	Kogi	2024	2,400	Operational
15	Transcorp-Ughelli Power Station	IPP	Gas	Delta State	1966	900	Partially
16	Sapele Power Station	IPP	GF- steam	Delta State	1981	1,020	Partially
17	Egbin Thermal Power station	IPP	GF- steam	Lagos State	1986	1,320	Partially
18	Omotosho I Power Station	NIPP	Gas	Ondo	2005	336	Partially
19	Geregu I Power Station	IPP	Gas	Kogi State	2007	414	Partially
20	Ibom	IPP	Gas	Akwa Ibom	2009	190	Partially
21	Afam VI Power Station	IPP	Gas	Rivers State	2010	642	Partially
22	Geregu II Power Station	NIPP	Gas	Kogi State	2012	434	Partially
23	Olorunsogo II Power Station	NIPP	Gas	Ogun State	2012	675	Partially
24	Omotosho II Power Station	NIPP	Gas	Ondo State	2012	450	Partially
25	Sapele	NIPP	Gas	Delta State	2012	450	Partially
26	Ihovbor Power Station	NIPP	Gas	Edo State	2013	450	Partially
27	Alaoji Power Station	NIPP	Gas	Abia State	2015	1,074	Partially
28	Afam IV-V	FGN	Gas	Rivers State	1982	977	Non-operational
29	AES Barge	IPP	Gas	Lagos State	2001	270	Non-operational
30	Eleme	IPP	Gas	Rivers State	2006	75	Non-operational
31	Egbema Power Station	NIPP	Gas	Imo State	2013	338	Non-operational
32	Calabar Power Station	NIPP	Gas	Cross	2014	561	Non-operational
33	Omoku II	NIPP	Gas	Rivers State	2012	225	Incomplete

Table 2: Status of Power Generation Stations in Nigeria

The Nigerian energy sector is plagued by several challenges, including insufficient generation capacity, transmission system constraints, power sector planning shortfalls, vandalism and weak investment regimes. Nigeria's energy infrastructure has not been developed to match and leverage the growing population and economic potential of the country over a long period. However, there are concerted efforts to increase the installed capacity by 2030 and beyond, and in addition improve the transmission and distribution infrastructure (Figure 6) with investment friendly policy initiatives. Some of the proposed policies includes:

- proper deregulation of the energy sector to allow sustainable electricity tariff
- encouraging local manufacture of electrical equipment and devices
- improving the operational efficiency of the electricity subsector
- promoting the development of the renewable energy components of the energy mix.

To address current and projected energy gaps, the federal government, some state governments, and private sector actors have proposed new power plant projects aimed at increasing available capacity (Table 3). The majority of these projects are gas- and coal-fired, non-renewable plants. Of the proposed 17,800 MW, only 3,260 MW would come from renewable sources, with the remaining 82% reliant on fossil fuels [32]. This underscores the need for a more pragmatic framework to fully harness Nigeria's renewable energy potential. Accordingly, this study seeks to identify pathways for the sustainable development of Nigeria's green hydrogen potential, with applications in the transport and power sectors, and, importantly, in agriculture through enhanced fertiliser production.

	Power Plants	Type	Location State	Planned Commission	Capacity (MV)	Status
1	Mambilla	Hydro	Taraba	2030	3,050	Stalled
2	Ashama	Solar	Delta	2023	200	Proposed
3	Qua Iboe	Gas	Akwa Ibom	2025	540	Stalled
4	Okpai/Kwale-Okpai	Gas	Delta	2031	450	Planning
5	Totalfinaelf (Obitex)	Gas	Rivers	2031	420	Planning
6	Anambra State IPP	Gas	Anambra	2031	528	Planning
7	Knox	Gas	Kogi	2031	501	Planning
8	Delta State IPP	Gas	Delta	2032	500	Planning
9	Benco	Gas	Bayelsa	2033	700	Planning
10	Kaduna	Gas	Kaduna	2034	900	Planning
11	Fortune Electric	Gas	Cross River	2035	1,000	Planning
12	Gwagwalada	Gas	Abuja	2037	1,350	Planning
13	Ashaka/TPGL	Coal	Gombe	2034	500	Planning
14	Ashaka	Coal	Gombe	2034	64	Planning
15	Nasarawa	Coal	Nasarawa	2034	500	Planning
16	Ramos	Coal	Delta	2034	1,000	Planning
17	Benue	Coal	Benue	2037	1,200	Planning
18	Enugu	Coal	Enugu	2037	2,000	Planning

Table 3: Proposed Power Generation Stations in Nigeria

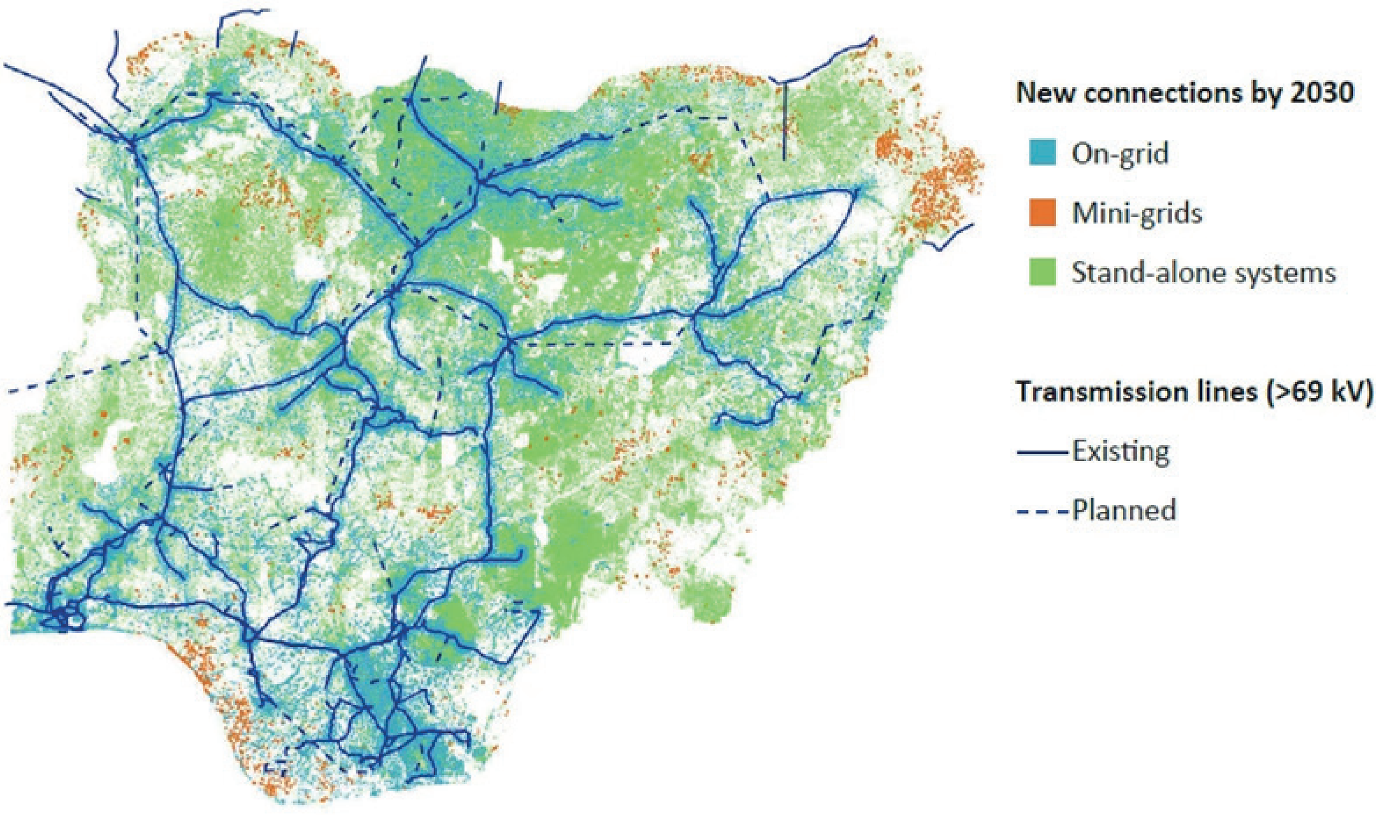

Figure 6: Nigeria electricity access solutions by type in the Africa Case[30]

1.3. Outlook on Nigeria's Energy sector

Despite the enormous potential, the Nigerian power system is characterised by a huge supply deficit. Whereas the estimated energy demand to deploy the full potential of her economic opportunities is put at more than 98,000MW, including latent and suppressed demand [33]. The 23 grid-connected generating plants operating in the Nigerian Electricity Supply Industry (NESI) have a total installed capacity of 16,384 MW and an available capacity of 7,139.6 MW. However, the highest ever dispatched power from the national grid is 5,615.40MW, with dispatch power normally less than 4000MW [34]. Moreover, the energy progress report posits that electricity access in Nigeria is about 61.19 % as of 2023, with 77 million (out of the total population of 195 million) people without a power supply [35]. Electricity access for the urban population was placed at 91.4% (where 51% of Nigerians live), while that of the rural population was placed at 30.4% (where 49% of Nigerians live). A study that classified Nigeria into 47,489 population clusters by land area found that 45,456 clusters (95%) are non-electrified. The majority of these non-electrified areas are off-grid, where extending the national grid is neither economical nor sustainable due to the high cost of transmission infrastructure (Figure 3).

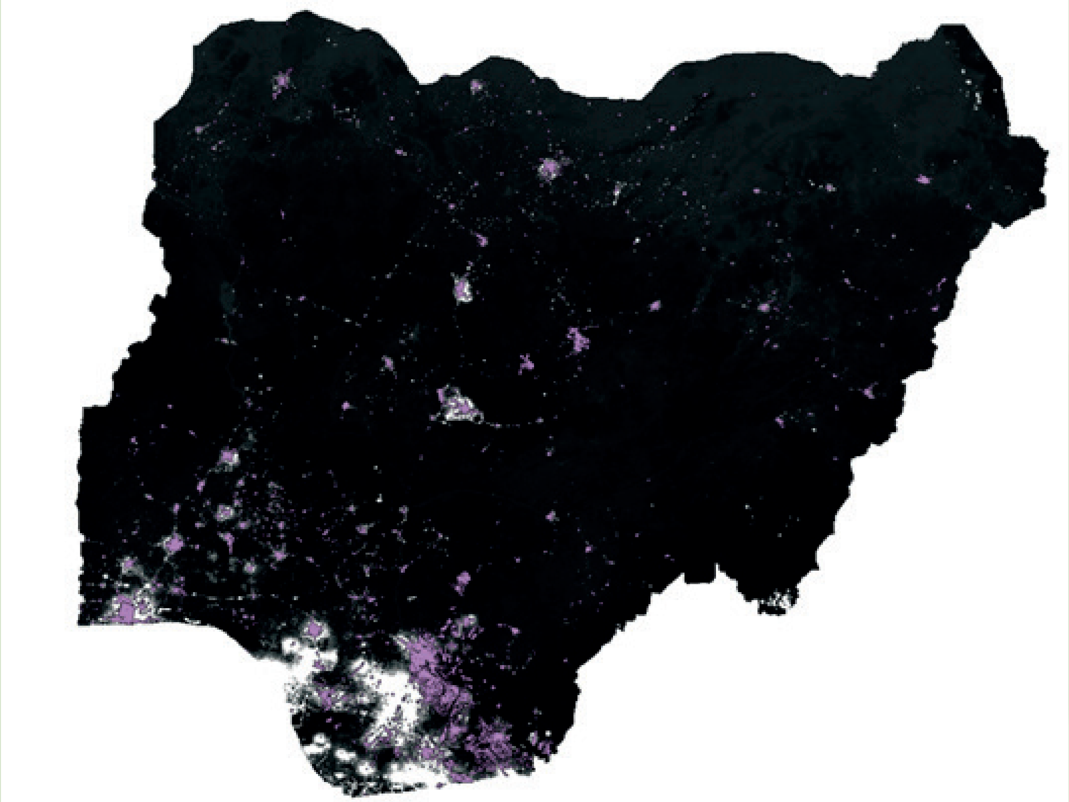

Figure 3: Geographical Distribution of Electrification [36]

Available energy in Nigeria is largely consumed in the residential sector, accounting for about 50% of final energy consumption. The industrial and transport sectors each make up a fifth, while the remainder supply the energy needs of the commercial and agricultural sectors (Figure 5). The low level of mechanisation is reflected in the negligible energy demand in the agricultural sector, which underscores the prevailing food insecurity and import reliance. If the government's policy reforms, particularly the net-zero strategy, are fully implemented, industrial and agricultural production is expected to account for a significant share of national energy demand. Meeting this demand from renewable energy sources would be the most sustainable approach.

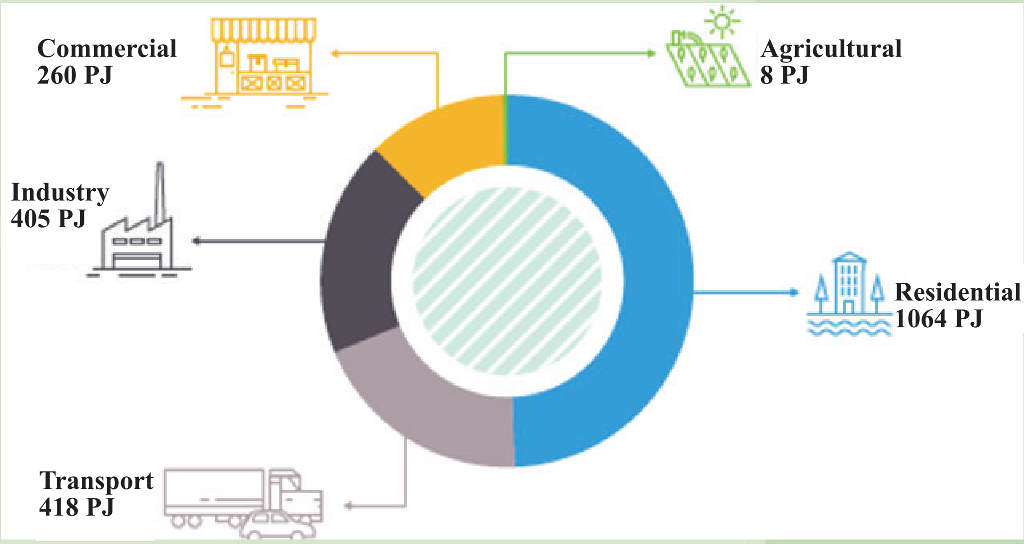

Figure 5: Nigerian energy consumption by sector [30]

2. NIGERIA GREEN HYDROGEN POTENTIAL

2. NIGERIA GREEN HYDROGEN POTENTIAL

2.1. Green hydrogen technologies and applications

Hydrogen is a chemical energy carrier with an energy content of 120- 142 MJ/kg (the highest energy content per unit weight of any known fuel) and produces no carbon emissions on combustion; hence, hydrogen is considered a potential replacement for primary energy sources. It is widely considered a fuel for the future and has therefore gained global interest in recent years. This is attributable to its potential to play a key role in the global push to cleaner energy sources and the decarbonization of the heavy carbon-emitting sectors.

2.1.1. Chromatic Scale of Hydrogen Production Technologies

Hydrogen is now generally characterised by colours, which vary depending on the energy source and technology used. As a result, there are several types of hydrogen which is influenced by its carbon footprint (emission intensity), direct and process water usage, energy requirements, and costs of production as presented in Figure 8.

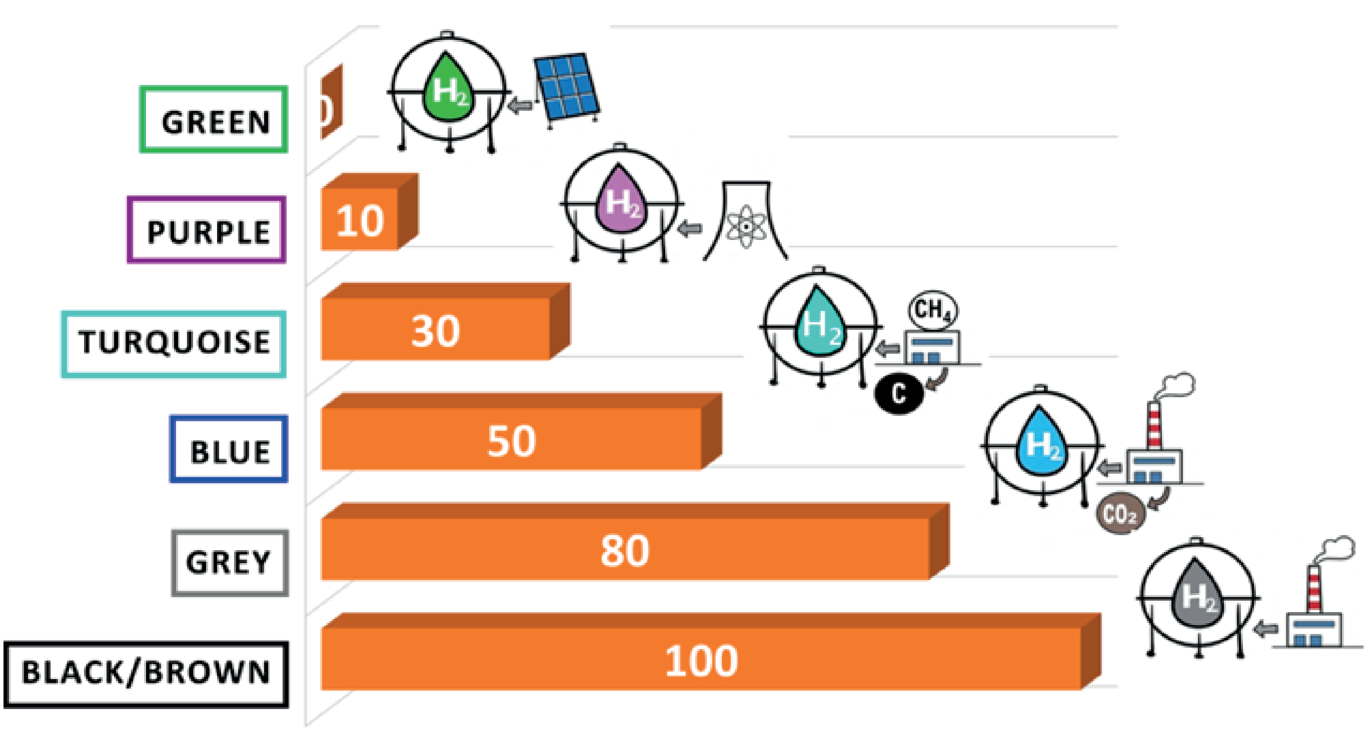

Figure 8: Selected hydrogen colour coding and associated carbon emissions with numbers indicating an arbitrary carbon footprint scale [37]

2.1.2. Green hydrogen production technologies/process

Green Hydrogen is produced through water splitting processes or biomass processing. Hydrogen production from water splitting can be in the form of electrolysis, thermolysis, or photolysis [40]. To date, only about 4% of hydrogen production comes from electrolysis. In the following section, the focus will be on green hydrogen production from water via electrolysis.

Hydrogen can be produced by splitting water in an electrolyser through the passage of a direct current. An electrolyser consists of an anode and a cathode separated by an electrolyte, and the quantity of hydrogen produced depends on the electrolyser's size, type, operating conditions, efficiency, and water purity. Electrolysers are classified according to the electrolyte material and the ionic species they conduct. The most commercially deployed types are the alkaline electrolyser and the proton exchange membrane (PEM) electrolyser. Emerging technologies, such as the anion exchange membrane (AEM) and solid oxide electrolyser (SOE), remain at early demonstration or pilot stages.

Proton Exchange Membrane (PEM) electrolysers use a solid polymer membrane as an electrolyte to split water into hydrogen and oxygen using electricity, typically from renewable sources. The PEM separates the anode and cathode, allowing protons (H^+ ions) to pass through while blocking gases, enabling efficient and high-purity hydrogen production. The operating temperature ranges from 50 to 80 °C, and the operating pressures can be set up to 30 bar.

Alkaline electrolysers, on the other hand, operate via transport of hydroxide ions through the electrolyte from the cathode to the anode, with hydrogen being generated on the cathode side [41]. Electrolysers using a liquid alkaline solution of sodium or potassium hydroxide as the electrolyte have been commercially available for many years.
Anion Exchange Membrane electrolyser uses a semipermeable anion exchange membrane that conducts negatively charged ions (anions, typically OH^-) through the membrane. Electrodes operate in an alkaline environment, allowing the use of low-cost transition metal catalysts instead of expensive platinum-group metals required by PEM electrolysers.

Solid Oxide Electrolyser is fed by Steam fed to the cathode side, where it is reduced to hydrogen gas and oxide ions (O^{2-}). The oxide ions migrate through the solid oxide electrolyte to the anode. At the anode, oxide ions are oxidised to form oxygen gas, which is released as a byproduct. The process uses electricity and heat, with the high temperature improving reaction kinetics and ionic conductivity, resulting in higher efficiency. Table 4 summarizes the different water electrolysis methods.

Electrolysis Method	Advantages Non-metal electrocatalytic	Disadvantages
Alkaline electrolysis	Energy efficiency: 65-67%(LHV) Low cost High durability Moderate operating Low capital cost Well suited for large scale	Low-purity H2 Limited current density Corrosive environment Low pressure 1–10 bar
Proton-exchange membrane water electrolysis	Energy efficiency: 61–65% (LHV) Ultra-pure H2 (99.99%) High current density Quick response and flexibility	High cost Scarcity of materials Low operating pressure Low lifespan Maintenance complexity Complex scalability
High-temperature electrolysis with solid oxide membranes	High Energy efficiency (20% higher than PEM/Alkaline efficiency) High operating pressure (500°C – 1000°C) High current density Non-metal catalysis Reversibility (can be operated as a fuel cell)	Large size Long start-up Low durability High Thermal Stress and Low Durability High cost
Anion Exchange Membrane	Low material cost Fast response Compact and modular: easily scalable High pressure ~35 bar High hydrogen purity (~99.9% up to 99.999% with dryers)	Low Membrane Stability and Durability Low Ionic Conductivity Complex Electrolyte and Water Management (formation of carbonate)

Table 4: Different water electrolysis methods [42], [43]

2.1.3. Uses and applications of hydrogen

Hydrogen is highly versatile and has significant potential for sector coupling, linking the power, transport, industrial, and heating sectors. Its applications are diverse, and its derivatives, such as ammonia, synthetic fuels, and methanol further expand its potential uses (Figure 10). Once produced, hydrogen can play a key role across multiple sectors [39].

2.1.3.1. Energy sector

In the energy sector, Hydrogen acts as an energy carrier, enabling long-term storage of surplus renewable electricity (from solar, wind, etc.), balancing supply and demand and enhancing grid stability. It can store energy in chemical form and be reconverted to electricity through fuel cells or gas turbines or heat on demand, supporting renewable energy integration.

2.1.3.2. Transportation sector

The decarbonization of the heavy-duty and long-range applications in the transport sector can be achieved by hydrogen as battery usage faces limitations. It can be used either directly in fuel cells or can be used to produce hydrogen-based e-fuel for terrestrial, maritime, and aeronautical applications.

2.1.3.3. Industrial sector

Industries in Nigeria that currently use, or are likely to use, hydrogen in the future include oil refining, ammonia and methanol production, as well as the broader petrochemical and chemical sectors. Heavy industries, often classified as hard-to-abate sectors due to their high-temperature heat requirements and energy-intensive feedstock needs, can benefit from the versatility of hydrogen. Hydrogen can also play a key role in significantly reducing industrial sector emissions. In Nigeria, six major refineries with varying capacities currently operate, all of which have substantial hydrogen requirements.

2.1.3.4. Agricultural sector

In the field of agriculture, hydrogen offers opportunities to reach a sustainable agricultural system as it is a key ingredient for the manufacturing of ammonia, which is green if the hydrogen used is green. This ammonia is afterwards used for green and sustainable fertilisers production, very essential to improve productivity.

2.1.3.5. Residential Sector

In the residential applications, hydrogen comes as a good alternative for Heating, clean cooking, electricity generation, as well as an energy storage medium. In homes, hydrogen can be utilized directly in modified gas stoves or boilers, blended with natural gas for heating, or converted into electricity and heat through residential fuel cells, providing reliable and low-emission power.

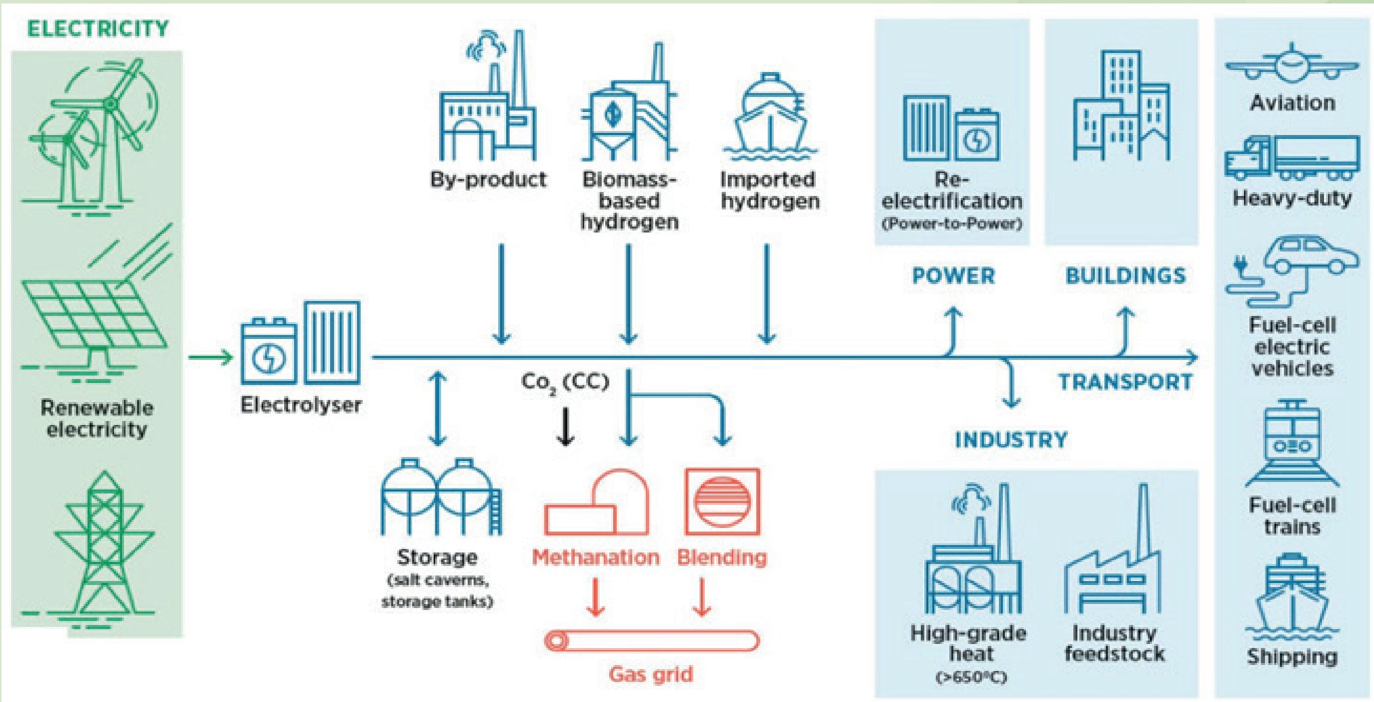

Figure 10: Green hydrogen value chain

2.2. Nigeria's green hydrogen potential from H2 Atlas project

The awareness of the importance of hydrogen and its derivatives has grown across Africa in the last four years since the launch of the H2Atlas-Africa project [42](Ballo et al., 2022). The study assessed the feasibility and potential for green hydrogen production across several African nations to support energy transitions towards more sustainable sources. The H2Atlas-Africa report showed that the vast land area of Nigeria and the huge renewable energy potential translate to a possible 16.000 TWh of green hydrogen annually.

The maximum technical hydrogen (H2) production potential per area, influenced by factors like available renewable energy resources (solar and wind), land availability, and the efficiency of electrolysis and storage technologies, ranges from 0 to 50.00 kWh/(yr*m²). The areas with the highest medium maximum technical hydrogen potential are located in the western, central, and eastern regions of the country, while the northern and southern regions exhibit the lowest values (Figure 11). Borno state has the highest maximum technical H2 potential, with values close to 50.00 kWh/(yr*m²). In this state, the absolute technical hydrogen potential is close to 500 TWh/yr.

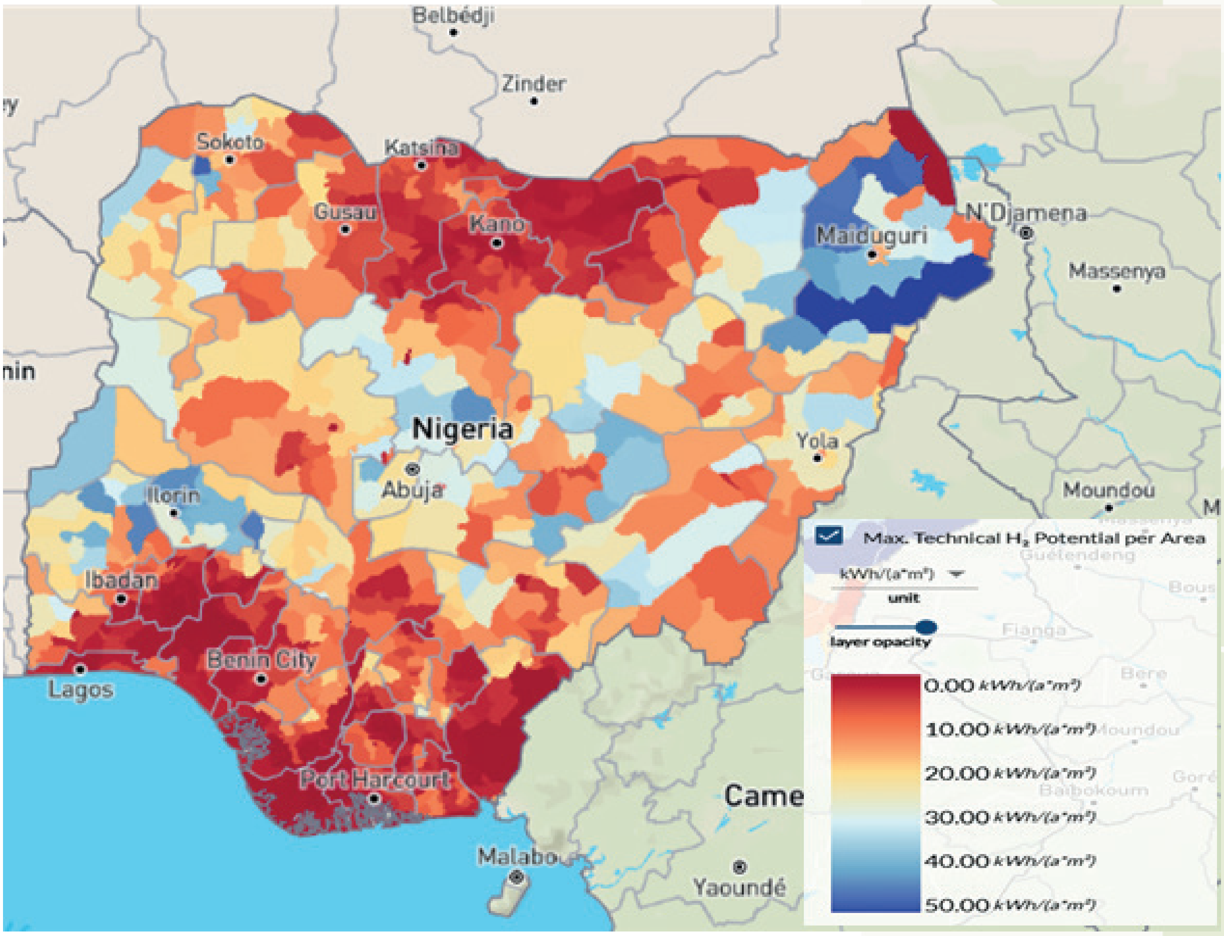

Figure 11: Annual Max Technical H2 potential per area [43]

Regarding the levelized cost (LCOH), depending on the locations and constraints, the projection in 2050 for green hydrogen production from Onshore wind and open-field PV power ranges from 1.7 to 3.7€/kg, as depicted in Figure 12.

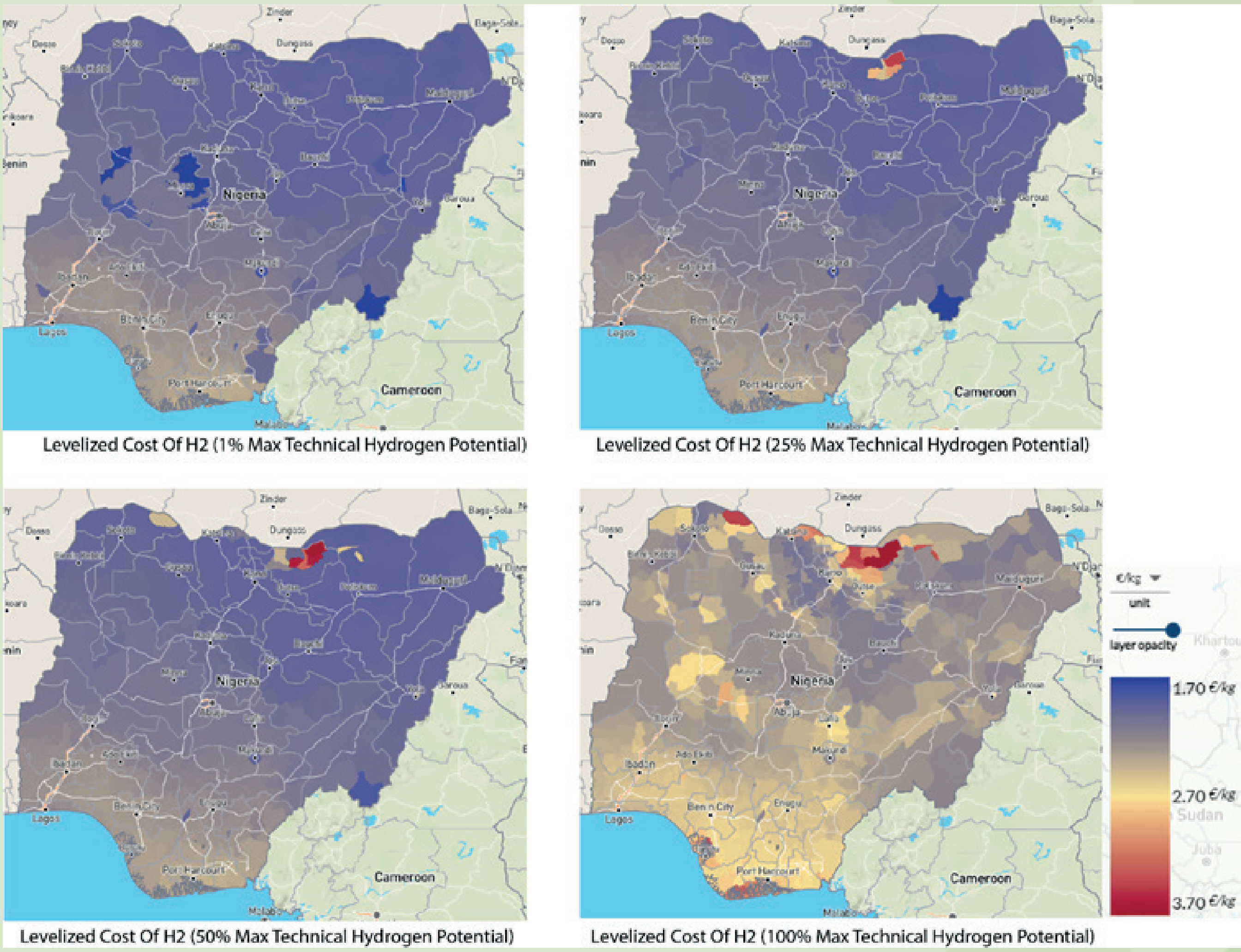

Figure 12: Projected Levelized Cost of H_2 in Nigeria in 2050

Considering groundwater as the water source for green hydrogen production, the H2 Atlas project evaluated the hydrogen producible from groundwater per Area, based on the "max. technical H2 potential per area. As shown in Figure 13, Borno State is the area where the highest H_2 producible from groundwater, close to 40.00 kWh/(yr.m²), was obtained. However, some areas located in the Central east, south and the western regions have H_2 Producible from Groundwater per Area close to 20 kWh/(yr.m2).

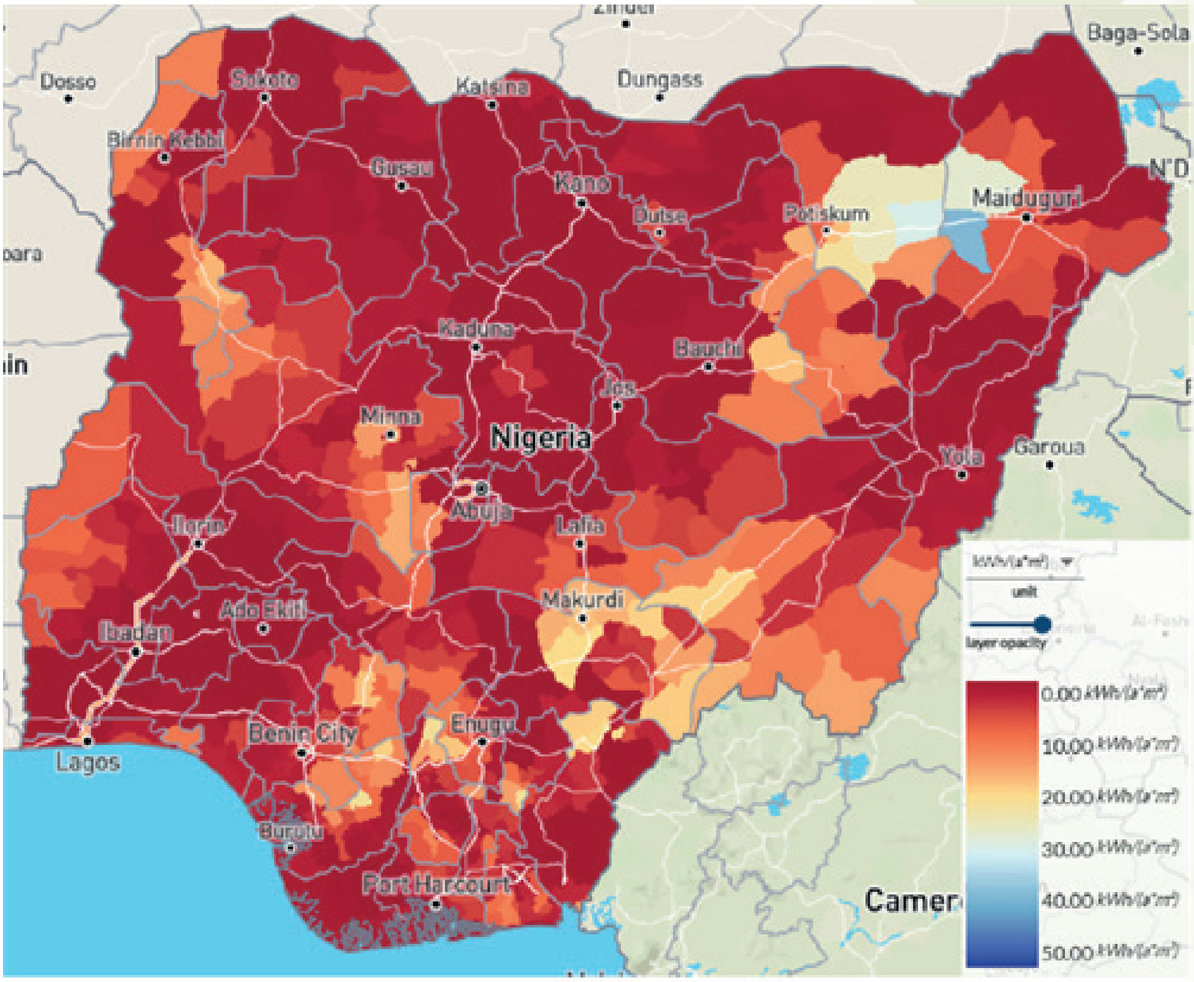

Figure 13: H_2 Producible from Groundwater per Area

Most applications of hydrogen are based on its derivatives. It can be combined with carbon from CO2 to produce a range of molecules. In its derivative forms, the energy density is increased further, which makes for a more cost-effective transport and storage. For instance, liquid ammonia has almost eight times the energy density (MJ/m3) of lithium-ion batteries and more than 20 times the gravimetric energy density (MJ/kg). Thus, about 55 % of the hydrogen produced around the world is used for ammonia synthesis, 25 % in refineries and about 10 % for methanol production. The other applications worldwide account for only about 10 % of global hydrogen production.

3. STAKEHOLDERS MAPPING

3. STAKEHOLDERS MAPPING

Various stakeholders with potential influence on Nigeria's emerging hydrogen economy have been identified and are summarised in the overview below. The list is not intended to be exhaustive.
Six main stakeholder categories, along with their respective subcategories, have been distinguished. A simplified illustration is provided in Figure 14. The main categories include: ministries and authorities, banks and investors, international stakeholders, active industries, service providers, and capacity-building organisations.

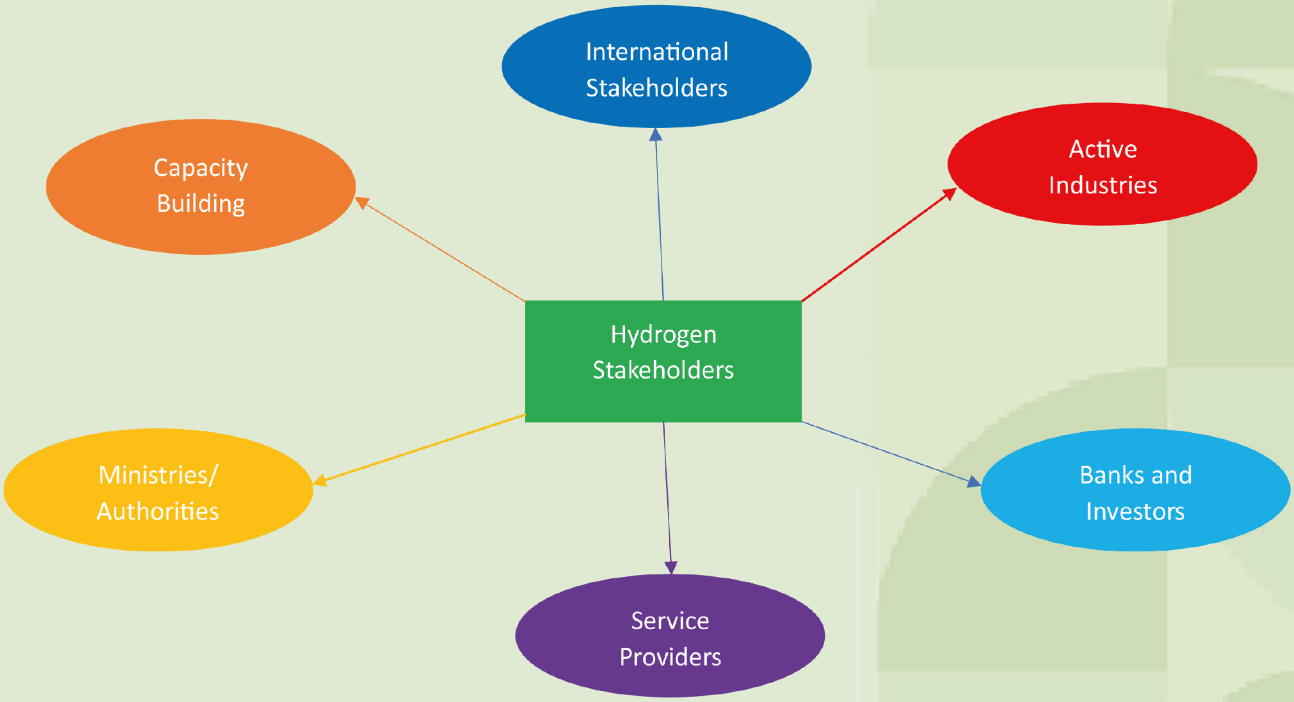

Figure 14: simplified map of identified Stakeholders for the green hydrogen economy in Nigeria

The successful development of hydrogen and, particularly green hydrogen, in Nigeria depends on the active involvement and collaboration of various stakeholders. These stakeholders can be categorised as follows:

3.1. State Actors

The most important stakeholders for the development of the emergent hydrogen economy in Nigeria are the Federal and State Government of Nigeria and their agencies. This is because:

- The Nigerian constitution vests the management and control of water resources, including surface and groundwater, in the Federal Government, particularly through the Water Resources Act 1993. The Federal Ministry of Water Resources and Sanitation, is the main government agency responsible for the management and control of water resources in Nigeria. An institutional framework comprising the River Basin Authorities and the National Water Resources Institute supports it [45]. The authority of the Minister of Water Resources over groundwater use includes the following:

- Authority over the timing, location, and manner of water use
- Determination of water allocations during periods of shortage
- Prohibition of water use for public health reasons
- Regulation of borehole construction and operation
- Revocation of water use rights in the public interest

In fulfilling its statutory responsibilities, the Ministry must ensure the provision of adequate and suitable water for domestic and non-domestic purposes, including livestock watering, agricultural irrigation, navigation, fisheries, and recreational use.

- In addition, Article 20 of the 1999 Constitution grants powers to the states of the federation over water resources management, stating: “The State shall protect and improve the environment and safeguard the water, air, land, forests, and wildlife of Nigeria.” Furthermore, groundwater ownership is linked to land ownership, which, under the Land Use Act of 1978, vests in the State Government. Moreover, hydrogen is classified internationally as an “energy carrier”, thus, its development is primarily viewed as an energy infrastructure development. Also under the 1999 Nigerian Constitution, amended in March 2023 (called Electricity Act 2023), the power to make law for energy development particularly, is shared between the Federal and State Governments. This act grant which repealed the “Electricity Power Sector Reform Act 2005 (“EPSRA”) allow both the State Government (hitherto vested in exclusively on the Federal Government) to make laws regarding electricity generation, transmission, and distribution, including in areas covered by the national grid, empowering them to regulate and manage their own electricity sectors[46].
- The Electricity Act 2023 crucially emphasised the generation of electricity from renewable energy sources. It encourages embedded generation, hybridised generation, cogeneration and the generation of electricity from solar energy, wind, small hydro, and biomass, all of which are very critical to the green hydrogen industry. The Act also promotes the development and utilization of renewable energy by providing a simplified licensing and fee structure for renewable energy service companies supplying electricity from renewable sources specified under the Act. Additional mechanisms to incentivize investment in renewable electricity are outlined in Section 164(a)–(u).Furthermore, the Act introduces tax incentives to promote and facilitate the generation and consumption of energy from renewable sources, in accordance with the provisions of the Industrial Development (Income Tax Relief) Act or any other fiscal policy framework that provides similar tax reliefs to encourage the implementation of renewable energy projects in Nigeria. Also, the Act introduces the feed-in-tariffs policy which guarantees a fixed price for renewable electricity f ed into the grid. In addition, the Act provides for opportunities for Embedded Generation, which requires power generating licensees to generate a certain approved percentage of their total power generation from hybridised generation or from renewable energy sources, such as solar energy, wind energy, small hydro energy, biomass, or such other renewable energy sources as defined under the Act or as may be developed in the future [46].

- Finally, the Electricity Act 2023 provisioned the establishment of the National Hydroelectric Power Producing Areas Development Commission (N-HYPPADEC)- a body corporate charged with the function of formulating policies and guidelines for the development of hydroelectric power producing areas without prejudice to the powers of the Minister to issue policy directives and the NERC's power to regulate the electricity industry under the Act. The N-HYPPADEC and its full functions are set out in section 89(a) – (h) of the Act, includ ing states in the formulation and implementation of policies to ensure sound and efficient management of the resources of the hydroelectric power producing areas; and tackle ecologi cal problems that arise from overloading of dams in the hydroelectric power producing areas and advise the Federal Government or the state government on the prevention and control of floods and environmental hazards. All these provisions will be essential for the Green Hydrogen Industry.

The 1999 constitution (on which Nigeria operates) vested the control and management of water resources on the Federal Government. The Water Resources Act 1993 (Cap W2) explicitly states that the right to use and control all surface and groundwater, and any watercourse affecting more than one state, is vested in the Federal Government.
Thus, the key ministries and agencies include:

- **Federal Ministry of Water Resources and Sanitation** –Mandated with the constitutional responsibility of managing Nigeria's water resources. The ministry also serves as the supervisory authority for the Nigeria Hydrological Services Agency (NIHSA), which is tasked with evaluating the country's surface and groundwater resources in terms of quantity, quality, distribution, and availability

- **Federal Ministry of Environment** – For its constitutional delegated role in setting and enforcing environmental standards, law and policies in water management and climate change mitigation, which directly impact water availability and quality. Very importantly, the ministry hosts the National Environmental Standards and Regulations Enforcement Agency (NESREA), an agency charged with enforcing environmental laws, guidelines, policies, standards, and regulations in Nigeria, including those related to water resources. This includes regulating pollution from industrial discharge, waste disposal, and other sources that can contaminate water bodies. They are also involved in monitoring and managing the impact of human activities on water ecosystems.
  Moreover, the ministry develops and implements national policies and strategies to address climate change, including the National Climate Change Policy for Nigeria 2021-2030, which aims to reduce greenhouse gas emissions and mitigate the socio-economic impacts of climate change. The ministry promotes sustainable development, including the management of national biosafety and the development of clean energy solutions. In addition, the ministry is the host ministry for the National Council on Climate Change (NCCC); the body that advises the President on climate change matters and coordinates the implementation of the National Climate Change Policy.

- **Federal Ministry of Innovation, Science and Technology (FMIST)** – is expected to serve a central role in green hydrogen development due to its constitutionally delegated mandate to promote research, development, and innovation on topics of national interest that impact Nigeria's economy. The ministry also supervises the Energy Commission of Nigeria (ECN), which is responsible for strategic planning and coordination of national energy policies, ensuring an adequate, reliable, cost-effective, and sustainable energy supply. According to the Energy Commission of Nigeria (ECN) Act No. 62 of 1979, as amended, the ECN is the apex government organ mandated to carry out overall energy sector planning, policy imple mentation, and promote diversification of energy resources, including new and alternative sources such as solar, wind, biomass, and nuclear energy. Biomass and Nuclear Energy.

- **Federal Ministry of Power** serves as a key end-user (offtaker/downstream) of green hydrogen when targeted for power generation, given its constitutional role in formulating and implementing policies for power provision, monitoring generation, transmission, and distribution, and guiding other ministries and agencies in the sector. It also oversees the Nigerian Electricity Supply Industry (NESI), guided by the National Electric Power Policy (NEPP) 2001, Electric Power Sector Reform (EPSR) Act 2005, Roadmap for Power Sector Reform 2010, and Electricity Act 2023.

- **Federal Ministry of Agriculture and Food Security** – acts as a principal end-user (offtaker/downstream) of green hydrogen when intended for fertilizer production, due to its mandate to develop and implement policies ensuring food security, provide raw materials for industry, and expand the agricultural sector as a contributor to national economic development.

- **Federal Ministry of Industry, Trade and Investment** plays a facilitative (enabler/midstream) role in green hydrogen development through its mandate to promote investment, foster partnerships, and support infrastructure and industrial development related to hydrogen production and utilization.

- **Federal Ministry of Budget and Economic Planning** – is responsible for facilitating (enabler/midstream) green hydrogen development by designing and implementing policies that drive economic growth and sustainability. Additionally, its mandate to align Nigeria’s economy with the Sustainable Development Goals positions it to support the diversification of the country’s energy portfolio in line with the Just Transition Framework.

In the context of Blue Hydrogen, several federal ministries and their agencies are strategic actors. They include:

- **Federal Ministry of Marine & Blue Economy** – serves as a key facilitator (enabler/midstream) for hydrogen development due to its mandate to leverage Nigeria's extensive marine resources to stimulate economic growth, enhance security, and promote environmental sustainability. Most agencies involved in maritime transport which is critical for green hydrogen export are domiciled in this ministry, including:

- Nigerian Maritime Administration and Safety Agency (NIMASA)
- Nigerian Ports Authority (NPA)
- Nigerian Shippers' Council (NSC)
- National Inland Waterways Authority (NIWA)

➡ **Federal Ministry of Petroleum (Gas)** – acts as a facilitator (upstream) in the blue hydrogen industry, overseeing the exploration and development of Nigeria's gas resources.

➡ **Nigerian Pipelines & Storage Company (NPSC)**) – With extensive experience in oil and gas pipeline and storage under the former NNPC, NPSC is positioned to be among the first operators in storing and transporting hydrogen and hydrogen-derived products via pipeline. Other potential players include:

- NNPC Shipping Limited (NSL)
- NNPC RefChem Limited (NRCL)
- National Energy Reserve Management Company (NERMC)

Critical parastatals for the hydrogen industry include:

⊙ **Nigerian Upstream Petroleum Regulatory Commission (NUPRC)** – Established under the Petroleum Industry Act (PIA), NUPRC regulates the oil and gas industry to ensure compliance with laws and standards. It has led transformative initiatives such as the National Gas Policy, the National Gas Expansion Programme, the Nigerian Gas Flare Commercialisation Programme (NGFCP), the Presidential Compressed Natural Gas (CNG) Initiative, and the ongoing Decade of Gas (2021–2030), all aimed at decarbonizing the oil sector and promoting natural gas as a transitional fuel in Nigeria's energy shift.

⊙ **Nigerian Midstream and Downstream Petroleum Regulatory Authority (NMDPRA)** – Created by the Petroleum Industry Act 2021, NMDPRA provides the legal, regulatory, governance, and fiscal framework for midstream and downstream petroleum and natural gas operations. The Authority sets and enforces standards for design, construction, operation, and maintenance of relevant facilities, ensuring security of supply, market development, and competition. With blue hydrogen derived from gas and green hydrogen transported as gas, NMDPRA serves as a key facilitator in the mid- and downstream segments.

⊙ **Nigerian Port Authority (NPA)** - The NPA governs and operates Nigeria's major ports, including Lagos Port Complex, Tin Can Island Port Complex (Lagos State), Calabar Port Complex (Cross River State), Delta Ports (Warri, Delta State), and Onne and Rivers Port Complexes (Rivers State). Operations are conducted under the supervision of the Federal Ministry of Marine & Blue Economy and in collaboration with other government agencies, supporting the transport and export of hydrogen

3.2. Private Actors and Interprofessional Associations

In the development of green hydrogen industry and the value chain Nigeria, some critical stakeholders in the private sector in Nigeria would be very critical. They would be very important as investors in the development of upstream infrastructure for green hydrogen production, e.g. renewable energy power plant, electrolyser plants; or in the midstream for hydrogen storage transport and handling and some in the downstream as offtakers of green hydrogen and the associated products like ammonia, methanol etc.
Key players comprise, among others:

- Power Generation Companies (GenCos): Indigenous power generating companies with ongoing investment on generating power from renewable energy source like Solar Farm, windmills etc. Existing Nigeria companies investing in renewable energy. Some of them are as presented herein.
- Transcorp Power (Transcorp PLC) - Nigeria leading power provider with combined installed capacity of approximately 2000MW accounting for 15.5% of the total installed capacity in Nigeria. The company recently began investing in renewable energy source to close the energy gap in Nigeria.
- Azura Power provides 752MW into the national grid, with a further 1,372MW of generating capacity which is in development. The company is developing Azura-Nova, the 100MW solar power plant on 200-hectare site in Katsina State, Nigeria.

- Husk Power Systems is the leading rural energy services company in weak-grid and off-grid communities in Africa and Asia. They provide reliable, quality, 100% renewable power to businesses, households and institutions and are currently developing a 250MW of Decentralized Renewable Energy Projects based on PV solar system. They have plan for 1,000 minigrids in Nigeria, and another 1,500 in other parts of Sub-Saharan Africa.
- Savannah Energy PLC (Renewable Energy Division) is an independent energy company focused supplying gas to approximately 20% of Nigeria's thermal power generation capacity. The Savannah's Power Division currently has up to 696 MW of renewable energy projects in motion in Nigeria and other neighbouring countries. They are involved across the entire project life cycle, taking projects from greenfield development through to long-term ownership and operation. The Division is currently managing 250 MW wind farm project, expected to be the largest in West Africa and a 35 to 40 wind turbines and a total power generation capacity of up to 250 MW, it is expected to produce up to 800 GWh of electricity per year. They will be good target of upstream investment in green hydrogen development.
- Starsight Power Utility Limited specialise in clean custom energy solutions for businesses in both the commercial and industrial sectors. Their business model of eliminating upfront capital costs for clean on-grid and off-grid energy solutions may be good for investment decision in Green Hydrogen production. With an installed generating capacity of 227MW, carbon reduction of 473,578Tonnes, 82MWh installed battery capacity 19,366HP and cooling capacity, the company is a leading renewable energy service provider.
- NNPC New Energy Limited (NNEL) – The company formed from the erstwhile Nigeria National Petroleum Corporation following passage the Petroleum Industry Act of 2021 has been aggressive in the pursuit of renewable energy development, incorporating the New Energy Limited (NNEL) to provide sustainable, low-carbon (carbon neutral fuels) energy solutions for end users through

investment in commercial production and supply Energy from Solar farms, Biofuels, Biodiesel, Biogas, wind etc., while engaging in caption capture - Greenhouse Gases (GHG) emission reduction projects and services.

- The Renewables Investment Platform for Limitless Energy (RIPLE) a wholly-owned renewable energy subsidiary Nigeria Sovereign Investment Authority is intending to be Sub-Saharan Africa's leading renewable power generation company with 300MW solar programme, to be co-located within Shiroro Hydroelectric Power Plant in Niger State.
- Total Energies has been diversifying its energy portfolio with increasing investment in renewable energies from Sun and the Wind. The company intend to attain electricity production of 120 TWh by 2030, mainly through the development of solar and wind power. Development of the green hydrogen in Nigeria may be an important factor to attract such investment.
- Electrolyser Technology Provider/Investor Companies (EleTeCos): Till date, there are no indigenous Electrolyser Services Companies in Nigeria. This suggest that the sector will be dominated by the foreign investors as technology providers. This will include the like of Thyssenkrupp Nucera, H2 Core Systems, Enapter, and Siemens Silyzer all of Germany, Hysata of Australia, PERIC Hydrogen Technologies Co., LONGi Hydrogen and Sungrow Power Supply Co., all of China among others.
- Hydrogen Storage and Transport Service Providers / Companies (HySPCos): Considering the prevailing business model for operators in the energy (oil and gas) sectors of Nigeria, most players in the green hydrogen upstream may operate in the midstream (storage and transport to shipment point). However, depending on offtake agreement in the export market, some offtakers may invest on storage and transport infrastructure.
- Hydrogen and its Derivative End User: As at today the most likely set of ready off takers for green hydrogen (if the prices are competitive) in Nigeria are the Fertiliser producing companies. This is due to install capacity limitation due too consistent shortage of gas, for production of hydrogen used in Ammonia synthesis. Interestingly, the demand for fertiliser product particularly in adjoining South America overlooking Nigeria is huge. This aligns with the object of this study to understand the readiness of Nigeria local market for produced green hydrogen. The possible critical stakeholders for this shall include:
    - Dangote Fertiliser Limited (DFL)- DFL is Africa's Largest Granulated Urea Fertiliser plant with a total production capacity of 3.0 million tons per annum (MTPA) of Urea and Ammonia. Although the project began its first phase of production in 2021, the average utilization rate improved but remains low at just 50% in 2023 (up from 32% in 2022) largely due to gas shortages . The company has been working hard to source gas signing Gas Supply and Aggregation Agreement (GSAA). According to estimate from the equation ($3H_2 + N_2 \rightarrow 2NH_3$), 177 kg of H_2 and 823 kg of N_2, are theoretically necessary to produce 1 ton of ammonia [47]. Thus, at the current capacity, 5.31MMT of Hydrogen will be required by DFL. If 30 % of this is supplied as green hydrogen, it will make the company more environmentally friendly. This is aside the ambitious plan by the company founder to double the capacity to 6.0 million tons per annum (MTPA)[48].
    - Indorama Eleme Fertiliser & Chemicals Limited (IFL) - a part of Indorama Corporation, a global manufacturing conglomerate operating across Asia,

Europe, Africa and Americas, operates the world's largest single train urea plant in Nigeria since June 2016. IFL used to be the largest fertiliser producer in Sub-Saharan Africa with a total capacity to produce c.2.8 million metric tons of granular urea. IFL's complex comprises of two 2,300 metric tons per day Ammonia Plant of Purifier Ammonia Process Technology by KBR-USA, two 4,000 metric tons per day Urea synthesis plant of ACES 21 Synthesis Process Technology by TOYO Corporation and two 4,000 metric tons per day Urea Granulation Plant of Spout Bed Fluidizing Technology by TOYO Corporation, Japan and associated utilities. This world-scale urea complex comprises of Urea-Ammonia facilities, Captive Port Terminal, 83km gas pipeline and associated infrastructure facilities. IFL commissioned the 83km pipeline connecting the plant with the feedstock supplier at a design capacity of 235 mmscfd to support natural gas requirements of 2 urea lines. Indorama Eleme Fertiliser & Chemicals Limited (IEFCL) faces gas supply limitations, impacting its fertiliser production, particularly for its Train 2 and Train 3 projects, which aim to expand urea production capacity [49].

- Notore Chemical Industries Plc (Notore) is one of the leading fertiliser and agro-allied companies in Africa with over 20 years of experience. Notore has a urea-producing plant in Onne, Rivers State, with a current annual design capacity of approximately 500,000 metric tons per annum (MTPA) of urea and 330,000 MTPA of ammonia. They also have an installed 2,000 MTD NPK blending plant. Operations at Notore is also affected by gas shortages [50]. The company has to sign multiple Gas Supply Agreements to stabilize production [51].

Therefore, a possible competitive supply of green hydrogen will be a great relief and boost fertiliser production in Nigeria.

3.3. Non-Governmental and International Partners Organizations

Some international and multinational organisation operating in Nigeria will also play an essential role in developing a robust green hydrogen economy. They include:

- o Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Nigeria office – GIZ has been working to provides tailor-made, cost-efficient and effective services for sustainable development. On green hydrogen development, GIZ Nigeria has been promoting programme and initiatives to help Nigeria formulate national green hydrogen strategies, including framework conditions, policies, and regulations. They commissioned the H2Uppp study that investigated potential end-uses of green hydrogen and forecasted green hydrogen demand trends in Nigeria. More importantly, they helped in starting the German-Nigerian Hydrogen Office that had been at the forefront of groundbreaking studies that to assess the potential for hydrogen in Nigeria and lay the foundation for a thriving green hydrogen sector.
- o Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Nigeria office – GIZ has been working to provides tailor-made, cost-efficient and effective services for sustainable development. On green hydrogen development, GIZ Nigeria has been promoting programme and initiatives to help Nigeria formulate national green hydrogen strategies, including framework conditions, policies, and regulations. They commissioned the H2Uppp study that investigated potential end-uses of green hydrogen and forecasted green hydrogen demand trends in Nigeria. More importantly, they helped in starting the German-Nigerian Hydrogen

Office that had been at the forefront of groundbreaking studies that to assess the potential for hydrogen in Nigeria and lay the foundation for a thriving green hydrogen sector.

- United Nations Industrial Development Organization (UNIDO) Nigeria – Through its Global Programme for Hydrogen in Industry (GPHI), UNIDO Nigeria supports net-zero industrial development by leveraging green hydrogen's potential. Current plans include studies on green hydrogen clusters to accelerate industrial uptake, with a focus on policy, standards, skills, innovation, financing, and coordination.
- The West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) is an intergovernmental organization mandated to strengthen the resilience and adaptive capacity of West Africa to the impacts of climate change. WASCAL unites twelve member countries—Benin, Burkina Faso, Cabo Verde, Côte d'Ivoire, The Gambia, Ghana, Guinea, Mali, Niger, Nigeria, Senegal, and Togo—and fulfills its mandate through research and innovation, capacity building, and the provision of climate and environmental services. Its work strongly emphasizes supporting evidence-based policies, promoting renewable energy, and advancing green hydrogen development. Through its Capacity Building Department, WASCAL implements a network of Graduate Studies Programmes (GSPs) that train the next generation of climate scientists and practitioners. These programmes equip students with the skills to design and implement effective adaptation and mitigation strategies. As part of this effort, WASCAL established the International Master's Programme in Energy and Green Hydrogen (IMP-EGH), focusing on four core areas hosted by leading universities in 04 member countries:
  - Economics, Policies, Infrastructures, and Green Hydrogen Technology – Université Cheikh Anta Diop, Senegal
  - Bioenergy, Biofuels, and Green Hydrogen Technology – University of Lomé, Togo
  - Photovoltaic and system Analysis for Green Hydrogen Technologies, Université Abdou Moumouni – Niger
  - Green Hydrogen Production and Technology/Geo-resources (Université Felix Houphouet Boigny – Côte d'Ivoire.

WASCAL develops research projects on green hydrogen and provides technical assistance to countries to develop their national strategies and pilot projects. WASCAL has also financed the development of the ECOWAS regional green hydrogen strategy.

- The Economic Community of West African States (ECOWAS) The ECOWAS has developed a regional green hydrogen policy to promote sustainable energy and economic growth. It aims to posi tion West Africa as a competitive hub for green hydrogen production. The organization has also designed action plans to support infrastructure, investment, and capacity building. These efforts align with ECOWAS's broader renewable energy and decarbonization strategies.
- Niger Basin Authority (NBA):Commissioned in 1980, the NBA's nine member states are Niger, Benin, Chad, Guinea, Côte d'Ivoire, Mali, Nigeria, Cameroon, and Burkina Faso.WASCAL contributed to the development of the ECOWAS Green Hydrogen Policy and Strategy Framework, thereby enhancing regional coordination and supporting West Africa's energy transition agenda. In addition, the institution develops and implements research projects on green hydrogen and provides technical assistance to its member countries in formulating national strategies and pilot initiatives .
- The Economic Community of West African States (ECOWAS) : with support from WASCAL and the German Federal Ministry of Technology, Research and Space, ECOWAS has developed a regional Green Hydrogen Policy to promote sustainable energy and economic growth. The policy seeks to position West Africa as a competitive hub for green hydrogen by advancing infrastructure,

investment, and capacity building, in line with its broader renewable energy and decarbonization strategies.

- o Niger Basin Authority (NBA): Commissioned in 1980, the NBA's nine member states are Niger, Benin, Chad, Guinea, Côte d'Ivoire, Mali, Nigeria, Cameroon, and Burkina Faso. Supports integrated basin development related to energy, water resources, agriculture, animal husbandry, fisheries, forestry, and transportation.
- o Lake Chad Basin Commission (LCBC): Established in 1964, members include Cameroon, Niger, Nigeria, Chad, the Republic of Central Africa, and Libya to coordinate the sustainable development and equitable use of Lake Chad, regional peace and security, and environmental conservation.

3.4. Training and Researchers Centres

Nigeria has a lot of Universities, Research Institutions and Research Centre of Excellence focused on energy research. There are six Energy Research Centres under the Energy Commission of Nigeria with specific Technical/Research roles. These are:

- o National Centre for Energy Research and Development (NCERD) at the University of Nigeria, Nsukka
- o Sokoto Energy Research Centre (SERC) at Usmanu Danfodiyo University, Sokoto
- o National Centre for Energy Efficiency and Conservation (NCEEC) at the University of Lagos
- o National Centre for Hydropower Research and Development (NACHRED) at the University of Ilorin
- o National Centre for Energy & Environment (NCEE) at the University of Benin
- o National Centre for Petroleum Research and Development (NCPRD) at the Abubakar Tafawa Balewa University, Bauchi

A limited number of centers focus specifically on hydrogen and future fuels. These include :

- o Hydrogen Research Institute (HRI), Bogoro Research Centre, Afe Babalola University (ABUAD) in Ado-Ekiti - dedicated to investigating Blue, White and green hydrogen production, processing, and storage as an alternative to traditional energy sources. The Institute is a member of the African Hydrogen Partnership
- o African Centre of Excellence in Future Energies and Electrochemical Systems (ACE-FUELS), Federal University of Technology Owerri, Nigeria. The centre focuses on four core areas of discipline namely; Clean and Future Energy, Electrochemical Systems, Nanotechnology and Corrosion Technology, which complement each order and prioritizes research and development; knowledge sharing and dissemination; community education, technical skills and capacity development.
- o The Federal Universities of Technology Akure and Federal Universities of Technology Minna, being host to WASCAL Graduate programme, have research areas focussed on Green Hydrogen development in Nigeria.
- o The National University Commission
- o The Federal University of Technology, Minna
- o College of Petroleum and Energy Studies Kaduna

Nigeria recently established through the Petroleum Technology Development Fund (the foremost capacity building organisation for Nigeria's energy sector) the College for Petroleum and Energy Studies Kaduna, which centralise Nigeria's energy research. The College has a Centre for Hydrogen and Future Fuels which is carrying in-depth applied research in the hydrogen value chain in partnership with reputable institution in Germany, United Kingdom and Japan.

4. CROSS-SECTORAL ASSESSMENT

4. CROSS-SECTORAL ASSESSMENT

4.1. Policy and regulatory framework

The transition to green hydrogen presents an unprecedented opportunity for Nigeria to address its pressing energy challenges, reduce carbon emissions, and diversify its economy. As a country endowed with vast renewable energy resources, including solar, wind, and water, Nigeria has the potential to become a key player in the emerging global hydrogen economy. However, the success of green hydrogen initiatives in the country depends heavily on the development and implementation of an enabling regulatory framework that supports hydrogen production, distribution, and utilization. Currently, Nigeria's regulatory landscape lacks specific provisions for green hydrogen. Existing policies around water, environment, gas, and renewable energy need to be revised or expanded to accommodate the unique requirements of green hydrogen production. Additionally, alignment with regional policies, such as the emerging ECOWAS Green Hydrogen Strategy, will be essential to ensure Nigeria's integration into the broader West African hydrogen ecosystem. This section examines the critical components of Nigeria's regulatory framework relevant to green hydrogen, including water management, environmental sustainability, and energy policy. It also explores the ECOWAS initiatives on the domestic hydrogen landscape and provides policy recommendations aimed at fostering the adoption and exploitation of green hydrogen in Nigeria.

4.1.1. Environmental and Renewable Energy Policies

Nigeria has embarked on various programmes and policy initiatives in trying to make its energy system efficient, with Renewable Energy (RE) forming the core of the reformation. However, the country's energy reforms within the ambit of RE suffer setbacks, owing to poorly utilized RE resources and the initiation of relevant policies. Consequently, these setbacks widen the gap between energy demand and supply [52]. Table 5 summarizes the various policy instrument, programs, and regulatory frameworks that is related to RE development in Nigeria

S\No.	Title of document	Issuing year
1	National Electric Power Policy (NEPP)	**2001**
2	National Energy Policy (NEP)	**2003**
3	National Economic Empowerment and Development Strategy (NEEDS)	**2004**
4	National Power Sector Reform Act (EPSRA)	**2005**
5	Renewable Electricity Policy Guidelines (REPG)	**2006**
6	Renewable Electricity Action Programme (REAP)	**2006**
7	National Biofuel Policy and Incentives	**2007**
8	Vision 20:2020	**2010**
9	Roadmap for Power Sector Reform, 2010, 2013 (Update)	**2012**
10	National Adaptation Strategy and Plan of Action on Climate Change for Nigeria (NASPA-CCN)	**2012**
11	Renewable Energy Master Plan, 2005, 2012 (Update)	**2013**
12	National Renewable Energy and Energy Efficiency Policy (NREEEP)	**2015**
13	Multi-Year Tariff Order (MYTO)	**2012**
14	Draft Rural Electrification Strategy and Plan (RESP)	**2015**
15	Intended Nationally Determined Contribution (INDC)	**2015**
16	Nigerian Gas Policy (NGP)	**2017**
17	Nigeria's Climate Change Act	**2021**
18	Nigeria Energy Transition Plan (NETP)	**2023**

Table 5: Existing RE support policies, programs, and regulatory frameworks in Nigeria [52]

While most of the policy guide frameworks emphasised the need to include RE in Nigeria's energy mix, some like the National Adaptation Strategy and Plan of Action on Climate Change for Nigeria (NASPA-CCN), Renewable Energy Master Plan, 2005, 2012 (Update), National Renewable Energy and Energy Efficiency Policy (NREEEP), Intended Nationally Determined Contribution (INDC), Nigeria's Climate Change Act and the Nigeria Energy Transition Plan (NETP) focused on the need to harness energy from renewable sources to combat climate change.

Fundamentally, Nigeria's environmental and renewable energy policies are governed by several key frameworks aimed at promoting sustainability, reducing greenhouse gas emissions, and integrating renewable energy sources. The National Renewable Energy and Energy Efficiency Policy (NREEEP) is premised on the fundamental rule that renewable energy and energy efficiency are crucial to national development goals and that the government has a prime role in creating the enabling environment for meeting the energy challenges facing the nation. Furthermore, it emphasizes that the dependence on oil can be reduced through the diversification of the nation's energy resources, aggressive research, development and demonstration (R D& D), human resources development, etc. The Renewable Energy Policy has amongst other things, five broad objectives which may be summarized as follows:

- To enhance energy security in the nation through diversifying the energy supply mix;
- To increase energy access especially in the rural and semi-urban areas;
- To facilitate employment creation and empowerment;
- To protect the environment and mitigate climate change and,
- To promote renewable energy technologies (clean energy solutions) like solar, wind, and biomass to diversify Nigeria's energy mix [53].

The National Environmental Standards and Regulations Enforcement Agency (NESREA) oversees the enforcement of environmental regulations, particularly focusing on pollution control, environmental impact assessments (EIA), and sustainable practices across various industries, including energy production. The National Climate Change Policy for Nigeria: 2021-2030 highlight the need to define a new multi-sectoral and dynamic framework to guide the country's initiatives to the developing challenges of climate change. Therefore, the policy prescribes sectoral and cross-sectoral strategic statements and actions, within a medium-term time framework, between 2021 and 2030, for pursuing a climate resilient national sustainable development. On these bases, the protection of the environment becomes essential for achieving the mission and the overall goals of this National Policy, which is ensuring sustainable development and a climate proofed economy through multi-stakeholder engagement and promoting a low-carbon, climate-resilient and gender-responsive sustainable socio-economic development. The expected outcomes of these goals include improved social, cultural, economic and ecological resilience; reduced greenhouse gas emissions; increased awareness of climate change impacts; enhanced and strengthened research, innovation and technology development; enhanced capacity to implement climate change related interventions at national, state and community levels. The Climate Change Act 2021 targets carbon reduction and sets ambitious goals for achieving Nigeria's commitment to the Paris Agreement. It calls for the transition to low-carbon technologies and emphasizes the need for greener industrial activities, which could include hydrogen production.

Green hydrogen production, which relies on renewable energy sources like solar or wind to electrolyze water, is inherently aligned with Nigeria's environmental goals of reducing carbon emissions and transitioning to cleaner energy. This clean energy approach supports the objectives of the NREEEP and Climate Change Act by offering a scalable solution to diversify Nigeria's energy portfolio while reducing its carbon footprint. Additionally, green hydrogen production could further align with NESREA's standards by minimizing industrial pollution, as hydrogen production has the potential to be a zero-emissions process when powered by renewable energy sources. Integrating hydrogen into the energy mix would bolster the country's environmental sustainability agenda, contributing to a more resilient energy system.

There are significant policy gaps in integrating hydrogen into Nigeria's renewable energy framework, despite the promising potential. Currently, there is no specific national policy dedicated to hydrogen production, storage, or distribution, even though renewable energy policies like the NREEEP promote clean technologies.

This lack of detailed regulations tailored to hydrogen creates a gap in incorporating this emerging energy source into Nigeria's broader clean energy strategy. Furthermore, there is regulatory uncertainty regarding hydrogen production and usage. The current environmental policies do not fully address the challenges related to hydrogen production, including safety standards, water usage, and waste management, which are critical for sustainable development. Additionally, there are limited incentives for green hydrogen projects. Existing renewable energy policies focus heavily on solar and wind energy, but offer little to no incentive structures for green hydrogen. This limits the ability of green hydrogen projects to attract investment and scale up. Integration with Nigeria's renewable energy grid is another challenge, as the current infrastructure lacks sufficient capacity. For hydrogen to be produced sustainably, investments in grid stability, renewable energy generation, and storage systems are needed to support its production using clean energy sources.

4.1.2. Gas and Petroleum Policies and regulatory framework

The Nigerian Gas Policy (NGP), introduced in 2017, is a core element of Nigeria's energy strategy aimed at maximizing the use of the country's abundant natural gas resources. It seeks to transition Nigeria from a crude oil-dependent economy to one that leverages natural gas for domestic and industrial energy needs. A key focus of the policy is reducing gas flaring by promoting gas use for energy production and industrial applications to minimize environmental pollution. The policy also emphasizes using gas for power generation to improve energy access and affordability across the country. Additionally, the NGP encourages industrial use of natural gas, promoting it as a key feedstock for industries such as petrochemicals and fertilisers.

Hydrogen can complement Nigeria’s natural gas strategy by providing integration opportunities, especially in the shift to cleaner energy. Hydrogen can be blended with natural gas in existing pipelines and infrastructure, reducing the carbon intensity of the gas supply and supporting the NGP's goal of transitioning to cleaner energy sources. Nigeria’s current natural gas pipelines can transport a mixture of hydrogen and natural gas up to certain limits, reducing emissions without requiring new infrastructure. The country’s existing gas infrastructure, including pipelines, storage, and distribution networks, can be adapted to facilitate hydrogen distribution, offering a cost-effective platform for scaling up hydrogen transport and storage. As the natural gas sector grows, there is also potential to produce blue hydrogen through methane reforming with carbon capture and storage (CCS), serving as a transitional step toward a more mature hydrogen economy. In the short term, Nigeria can utilize natural gas for steam methane reforming (SMR) to produce hydrogen, and integrating CCS technology can reduce emissions, allowing for the production of blue hydrogen until green hydrogen becomes more cost-competitive.

To integrate hydrogen into Nigeria’s energy mix and capitalize on its natural gas infrastructure, several policy interventions are needed. The NGP should be amended to explicitly address hydrogen as part of Nigeria’s future energy strategy, including provisions for hydrogen blending, blue hydrogen production, and long-term green hydrogen development. Clear regulatory frameworks for hydrogen production, storage, and transportation will be essential to guide public and private investments. The government should establish standards that allow hydrogen to be blended with natural gas in pipelines, which international standards suggest can be done safely up to 20% without significant infrastructure changes. Incentives such as tax breaks or subsidies should be implemented to promote the adoption of CCS technologies for blue hydrogen production.

A national infrastructure plan should be developed to identify areas where hydrogen production can be integrated with existing natural gas infrastructure. This plan should address pipeline upgrades, storage, and transportation networks to support the long-term scale-up of hydrogen. Investment in research and development (R&D) should explore the feasibility of blending hydrogen with natural gas and transporting pure hydrogen through current gas pipelines. Public-private partnerships (PPP) should be encouraged to finance hydrogen projects, leveraging Nigeria's expertise in natural gas. While blue hydrogen offers a transitional solution, the policy should include long-term goals for transitioning to green hydrogen using Nigeria's renewable resources, gradually reducing reliance on natural gas, and increasing investments in green hydrogen production through renewable energy-powered electrolysis.

4.1.3. Water Policy and regulatory framework

Water is a fundamental resource for the production of green hydrogen, primarily through the process of electrolysis, which splits water into hydrogen and oxygen. In Nigeria, the primary water policies are governed by the National Water Resources Bill (2020) and the National Water Policy (2004) [54], [55]. These policies outline the framework for water management, emphasizing sustainable use, equitable distribution, and protection of water resources. The National Water Resources Bill aims to enhance water governance and promote the integration of water resources into national planning and development.
However, these policies do not explicitly address the requirements of hydrogen production, which necessitates a focused approach to water allocation. Given Nigeria's diverse climate and hydrology, effective water resource management is essential to support hydrogen production while also meeting the needs of agriculture, domestic use, and other industrial sectors.

4.1.4. Fertiliser Policy and regulatory framework

Agriculture is the mainstay of the Nigerian economy and contributed about 55.8 percent of Nigeria's GDP while generating about 64.5 percent of total export earnings in the past (1960 to 1z970) [56]. However, its contribution witnessed a steady decline, with the GDP fell as low as 21.5 percent in 2018, while it contributed about 22.72 percent to Nigeria's GDP in 2023 [57]. The decline has been occasioned by a shift towards oil revenue, and a decline in agricultural productivity due to poor soil conditions. Presently, however, population growth and declining soil fertility have necessitated fertiliser-intensive techniques of crop production, thus some policies have been developed to guide their sourcing and usage. Two fertiliser-related policies, the Agricultural Transformation Agenda (ATA) (2010/11-2016) and the Agricultural Promotion Policy (APP) (2016-2020), aim to enhance agricultural productivity, food security, and the livelihoods of Nigerians. However, these policies have faced inconsistencies due to changes in government regimes and agricultural subsidy programs [58]. The lack of consistency and continuity in Nigerian fertiliser policies has negatively impacted supply chains, logistics, distribution costs, fertiliser prices, farmers' access to inputs, and overall crop productivity. Despite being a major fertiliser producer in sub-Saharan Africa, Nigeria experiences low fertiliser consumption and farm application rates. Poor road infrastructure, credit constraints, inadequate extension services, high fertiliser prices, limited access to information, and inadequate quality control further hinder the efficiency of fertiliser supply chains.

Unwholesome political practices in Nigeria in relation to fertiliser subsidy programs have also ensured that aims and targets of the agricultural development policies remains a mirage [59]. To address these challenges, the newly adopted National Agricultural Technology and Innovation Policy (NATIP) builds upon ATA and APP which was aimed to gradually deregulate the fertiliser sector and encourage private sector investments in local production and distribution. The policy focuses on providing incentives for local fertiliser manufacturing, leveraging the gas industrialization policy, and promoting private sector participation in the distribution system.

One major goal of the various policy instrument is the promotion of local production in order to bring down cost. However, Nigeria has three urea production plants, namely Notore, Indorama, and Dangote, with a collective capacity of 6.5 million metric tons are only able to produce 3.65 million Metric Tons (MT) of urea in 2023 largely due to shortage of natural gas, which is a crucial constituent material used in Urea production (ammonia synthesis) [60]. Therefore, developing a pathway to generate green hydrogen would enhance location production, which will improve production.

4.1.5. Transport Policy: Energy and the Environment

Transport plays a key role in the economic and social development of any nation. Thus, section 8.2 of the key policies thrusts of the Draft National Transport Policy for Nigeria was to achieve an "environmentally sound transport system", means that reasonable, effective actions will be taken to diminish atmospheric, water and other pollution, through proper planning of infrastructure and the establishment of appropriate regulatory standards. The goals and objectives of this section of the policy are to:

- o To develop transport infrastructure which environmentally sustainable and in line with global best practice, with internationally accepted standards. Government through the Federal Ministries of Transport and Environment, and the Energy Commission of Nigeria;Develop transport infrastructure that is environmentally sustainable and aligned with global best practices and internationally accepted standards, through the collaboration of the Federal Ministries of Transport and Environment, and the Energy Commission of Nigeria.
- o Adopt and implement joint measures to reduce the negative impacts of transport on the environment.
- o Strengthen the institutional capacity of the Federal Ministries of Transport and Environment, as well as the Energy Commission of Nigeria, to safeguard environmental quality against transport-related pollutants.

Proposed strategies

- o To limit the consumption of fossil fuels using appropriate policy measures.
- o To promote rail and inland waterway mass transit services will provide the public with alternative transport choices to reduce the consumption of fossil fuels.
- o To introduce differential pricing for diesel, leaded and unleaded fuel petroleum modified spirit (PMS) to encourage more efficient and more environmentally-friendly fuels.
- o Promote additional strategies to mitigate the environmental effects of transport.
- o To promote environmentally sustainable investment decisions.

  Proposed Strategies:

- o Limit fossil fuel consumption through appropriate policy measures.
- o Promote rail and inland waterway mass transit systems to provide sustainable public transport alternatives

o Introduce differential pricing for diesel, leaded, and unleaded fuel (PMS) to incentivize the use of more efficient and environmentally friendly fuels.
o Encourage the adoption of renewable energy sources for transportation.
o Promote environmentally sustainable investment decisions within the transport sector.

Although these policy strategies did not directly suggest the use of green hydrogen, the green hydrogen value chain will greatly benefit from the use of renewable resources as fuels thereby promoting environmentally sustainable investment decisions.

4.1.6. ECOWAS Renewable Energy and Green Hydrogen Policies

The Economic Community of West African States (ECOWAS) recognizes the potential of renewable energy, including green hydrogen, to boost energy security, decrease reliance on fossil fuels, and promote sustainable development in the region. The ECOWAS Renewable Energy Policy, introduced in 2013, provides a framework for increasing the share of renewable energy in member states' energy mix and facilitating the deployment of technologies that harness renewable resources. The ECOWAS Green Hydrogen Policy builds on this, aiming to foster regional cooperation and development in the hydrogen sector. For Nigeria, participation in these initiatives offers an opportunity to develop its domestic hydrogen industry while positioning itself as a leader in West Africa’s hydrogen economy.

In recent years, with the technical and financial support of WASCAL, ECOWAS has developed a strategy specifically focused on green hydrogen, leveraging the region’s abundant renewable resources, especially solar and wind, for hydrogen production both for domestic use and export. The ECOWAS Green Hydrogen Policy outlines several objectives, including promoting the construction of infrastructure for hydrogen production, storage, and distribution, encouraging investment in hydrogen technologies, and enhancing technical expertise across member states. The policy also aims to standardize regulations across the region to facilitate cooperation and trade in hydrogen and ensure that hydrogen production aligns with environmental sustainability goals, such as those outlined in the Paris Agreement. A key focus of the ECOWAS Green Hydrogen Policy is regional cooperation to build a robust hydrogen economy. Member states are encouraged to collaborate on joint hydrogen production and infrastructure projects, share knowledge through regional forums and working groups, and develop cross-border trade policies that enhance energy security and economic integration. ECOWAS is also seeking international funding to support hydrogen initiatives and is organizing capacity-building programs to equip stakeholders with the necessary skills for the growing hydrogen sector.

Nigeria, as one of West Africa’s largest economies, stands to gain significantly from ECOWAS's Green Hydrogen Policy and related initiatives. Increased investment opportunities in hydrogen infrastructure could attract foreign and local investors, while access to technical expertise through ECOWAS programs would help Nigeria strengthen its hydrogen production capabilities. A regional hydrogen market could open new economic avenues for Nigeria, enabling it to export green hydrogen to neighbouring countries. Harmonizing its regulations with those of other ECOWAS member states would reduce trade barriers and facilitate smoother cross-border operations. By aligning its hydrogen production with ECOWAS’s environmental sustainability goals, Nigeria could enhance its international standing and attract further investments, while also improving its energy security by diversifying its energy sources and reducing its dependence on fossil fuels.

In summary, although green hydrogen may not have been directly featured as a topic in the many policies document on decarbonising several key sectors of the Nigerian economy, there is a concurrence on low carbon footprint and climate friendly pathways. Green hydrogen constitutes about the best option of achieving most of the objective of Nigeria policy of energy transition.

4.1.7. National Green Hydrogen Strategy of Nigeria

With the support of GIZ, Nigeria is developing a National Hydrogen Policy to advance its clean energy future and achieve net-zero emissions by 2060. The policy aims to leverage Nigeria's abundant renewable energy resources and existing oil and gas infrastructure to become a leader in the African green hydrogen market.

4.2. Infrastructure

INigeria is in the early stages of developing a hydrogen economy, with green hydrogen receiving a mention only in the last few months. However, because of the abundance of natural gas and renewable energy, it already possesses some infrastructure that could be leveraged and conditioned with appropriate technology to support the emerging hydrogen industry. This infrastructure includes renewable energy production facilities, storage systems, distribution networks, and transportation networks, all of which can be adapted or expanded for green hydrogen production, storage, and distribution. Below is a breakdown of the existing infrastructure that can support green hydrogen development.

4.2.1. Renewable Energy Production Infrastructures

Nigeria has made some strides in renewable energy development particularly hydropower, which is critical for green hydrogen production. Key existing infrastructures include:

- Solar Energy: Nigeria has an estimated solar energy potential of 5–7 kWh/m²/day, with few solar farms already operational. This includes the 10 MW Kano Solar Power Plant and the 1.2 MW Usman Dam Water Treatment Solar Power Plant. Although these are relatively small-scale projects, considering the massive potential of Nigeria. These facilities provide a foundation for scaling up solar-powered electrolysis for green hydrogen production.
- Hydropower: Nigeria's hydropower installed capacity is more than 2.0 GW from large hydro and about 60 MW of small hydro, with major plants like the Kainji Dam (760 MW), Jebba Dam (576 MW), and Shiroro Dam (600 MW). Nigeria has a hydro potential of around 24 GW and a small hydro potential of about 3.5 GW, which is yet to be exploited. Hydropower will be key in balancing the centralized power system by offering flexibility to mitigate solar power variability and would be a good source of generating green hydrogen. The transforming energy scenario (TES) according to the Renewable Energy Roadmap: Nigeria from the International Renewable Energy Agency (IRENA) Nigeria sees hydropower reaching 13 GW in 2030 and 15.5 GW in 2050 [32]. This represents an enormous potential to develop commercial green hydrogen production in Nigeria.

- o Wind Energy: Wind energy potential is concentrated in the northern regions with wind speeds of 4–6 m/s. Small-scale wind projects, such as the 10 MW wind turbine in Sayya Gidan Gada, Sokoto, demonstrate the feasibility of wind-powered electrolysis. The coastal regions of Nigeria also have potential, but as of the moment, there are major offshore wind projects in Nigeria.

Nigeria does not have dedicated infrastructure for green hydrogen production (Renewable energy plants, Electrolysers). The existing renewable energy infrastructures are for electricity production to supply the national electricity demand. However, they can constitute a base experience for new developments.

4.2.2. Infrastructure for Green Hydrogen Storage

Nigeria do not currently have any hydrogen storage infrastructure, although it is projected to have the potential to store hydrogen geologically in salt caverns, depleted oil and gas reservoirs, and aquifers. However, Nigeria has good experience working with Natural Gas with a network of liquified petroleum gas depots/terminal (Figure 15, Figure 16 & Table 6) and a 22 million tonnes per annum liquified natural gas (LNG) plant in Bonny Island (Figure 17). The LNG plant owned by NLNG also produces 5 million tonnes of natural gas liquids from its six trains. NLNG has been at the forefront of the global liquefied natural gas (LNG) industry, rapidly growing from a two-train plant in 1999 to a six-train facility in just nine years, earning a reputation as the fastest-growing LNG company in the world.

Figure 15: The 12MMSCFD Modular LPG Extraction Plant built by First Otakikpo Midstream Limited at the Otakikpo Marginal Field in Rivers State

The NLNG has 2 export jetties—one handling both LNG and LPG, and the other handling LNG and condensates, capable of supporting over 400 loadings per year. It equally has dedicated fleet of 23 LNG ships that ensure the reliable delivery of products to global markets and materials offloading jetty dedicated to receiving essential materials required for plant operations. The experience of Nigeria in developing these LPG and LNG plants as well as their terminal will be handy in developing plant and terminal for green hydrogen. Moreover, some the plant or terminal may be reconfigured in the future to handle hydrogen derivative like green methanol and green ammonia. Natural Gas Infrastructure: Nigeria's existing natural gas infrastructure, including pipelines and storage facilities, can be repurposed for hydrogen storage and transportation. For example, the Escravos-Lagos Pipeline System (ELPS) and the Ajaokuta-Kaduna-Kano (AKK) Gas Pipeline could be adapted for hydrogen use (see Figure 15). Industrial Storage Facilities: Industries such as oil refining and petrochemicals have existing storage tanks that can be retrofitted for hydrogen storage.

Figure 16: The newly completed 24,000 Metric Tons Ardova Plc LPG Terminal in Ijora, Lagos State

Figure 17: The 22 million tonnes per annum Nigeria liquified natural gas (LNG) plant in Bonny Island, Rivers State Nigeria

	LPG Depots/Terminals	Address	Installed Capacity (MT)	Status:
1	Navgas LPG Terminal/D	23, Creek Road, Apapa, Lagos, Nigeria	12,000	**Active**
2	Nipco Plc LPG Terminal/Depot	Address: 1-15, Dockyard Road, Apapa, Lagos, Nigeria	11,000	**Active**
3	Techno Oil LPG Terminal/Depot	Tank-farm & Jetty Terminal, Mosheshe Industrial Layout, Kirikiri Lighter Terminal, Phase 2, Apapa, Lagos, Nigeria	8,400	**Active**
4	Rain Oil LPG Terminal/Depot	2, Pioneer Drive, Off Marwa Road, Off Old Ojo Road, Ijegun, Satellite Town, Lagos, Nigeria	8,000	**Active**
5	Rain Oil LPG Terminal/Depot	Oghara, Apapa, Delta State, Nigeria	6,000	**Active**
6	Matrix Energy LPG Terminal/Depot	Ifiekporo, Delta State, Nigeria	5,000	**Active**
7	Stockgap LPG Terminal/Depot	Rumuelumeni, Port-Harcourt, Rivers State, Nigeria	8,000	**Active**
8	AA Rano LPG Terminal/Depot	24, Pioneer Way, Satellite Town, Ijegun, Lagos State, Nigeria	20,000	**Active**
9	NPSC LPG Terminal/Depot	Kayode Road, Badia, Lagos State, Nigeria	7,000	**Inactive**
10	Shafa Energy LPG Terminal/Depot	Ifiekporo, Warri, Delta State, Nigeria	4,000	**Active**
11	Oredo LPG Processing Plant	Oredo, Benin, Edo State, Nigeria	2,600	**Active**
12	KHL Kwale Hydrocarbon LPG Terminal			**Active**
13	Dozzy LPG Terminal/Depot	Calabar, Cross-Rivers State, Nigeria	6,000	**Inactive**
14	Dangote Petrochemical LPG Processing Plant/Terminal	Lekki Free Zone, Ibeju-lekki, Lagos State, Nigeria	397,290	**Active**
15	Ardova Plc LPG Terminal/Depot	Ijora, Lagos State, Nigeria	20,000	**Active**
16	Asiko Energy LPG Terminal/Depot	Ijora, Lagos State, Nigeria	5,000	**Active**

Table 6: LPG plant/terminal in Nigeria

4.2.3. Infrastructure for Green Hydrogen Transport and Distribution

There are no hydrogen pipeline or vending station, but because of the abundance of natural gas, Nigeria have considerable natural gas pipeline network and LPG dispensing stations that could be leveraged, repurposed and utilized for hydrogen distribution, particularly in industrial clusters and urban centres. According to date available from the Nigerian Gas Processing and Transportation Company Limited (NGPTC), the network consists of 14 Gas Compressor, 20 Metering Stations, and about 1,990 km of gas pipelines and related facilities capable of transporting about 3.5 Billion scf/d within the nation (Figure 18, Figure 19 & Figure 20) [61]. There is an ongoing 614 kilometres Ajaokuta–Kaduna–Kano Natural Gas Pipeline project that is to extends natural gas resources to sustainably supply gas to northern Nigeria (Figure 21). The development is expected to reduce the quantity of gas flared in the country's oil fields and thus improve air quality. The experience would surely help in hydrogen distribution in Nigeria.

Figure 18: Map of Nigeria Existing Gas infrastructure including end users - Western and Eastern Gas Pipeline Networks [62]

Figure 19: Map of Nigeria Existing Gas infrastructure including end users - Western Pipeline Network [62]

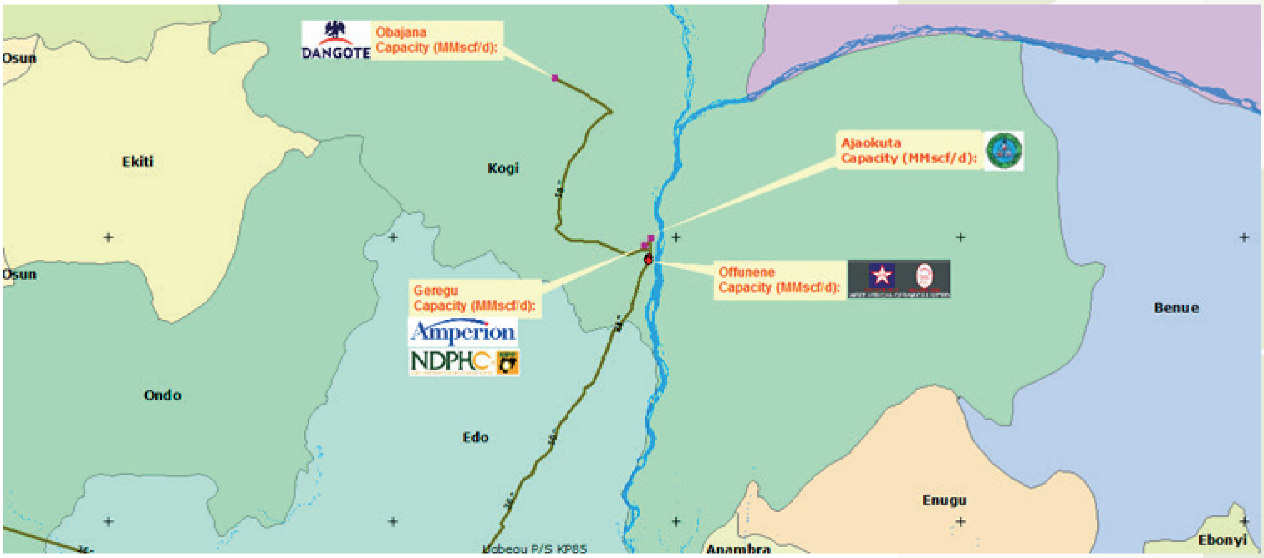

Figure 20: Map of Nigeria Existing Gas infrastructure including end users - Northern Gas Pipeline Network [62]

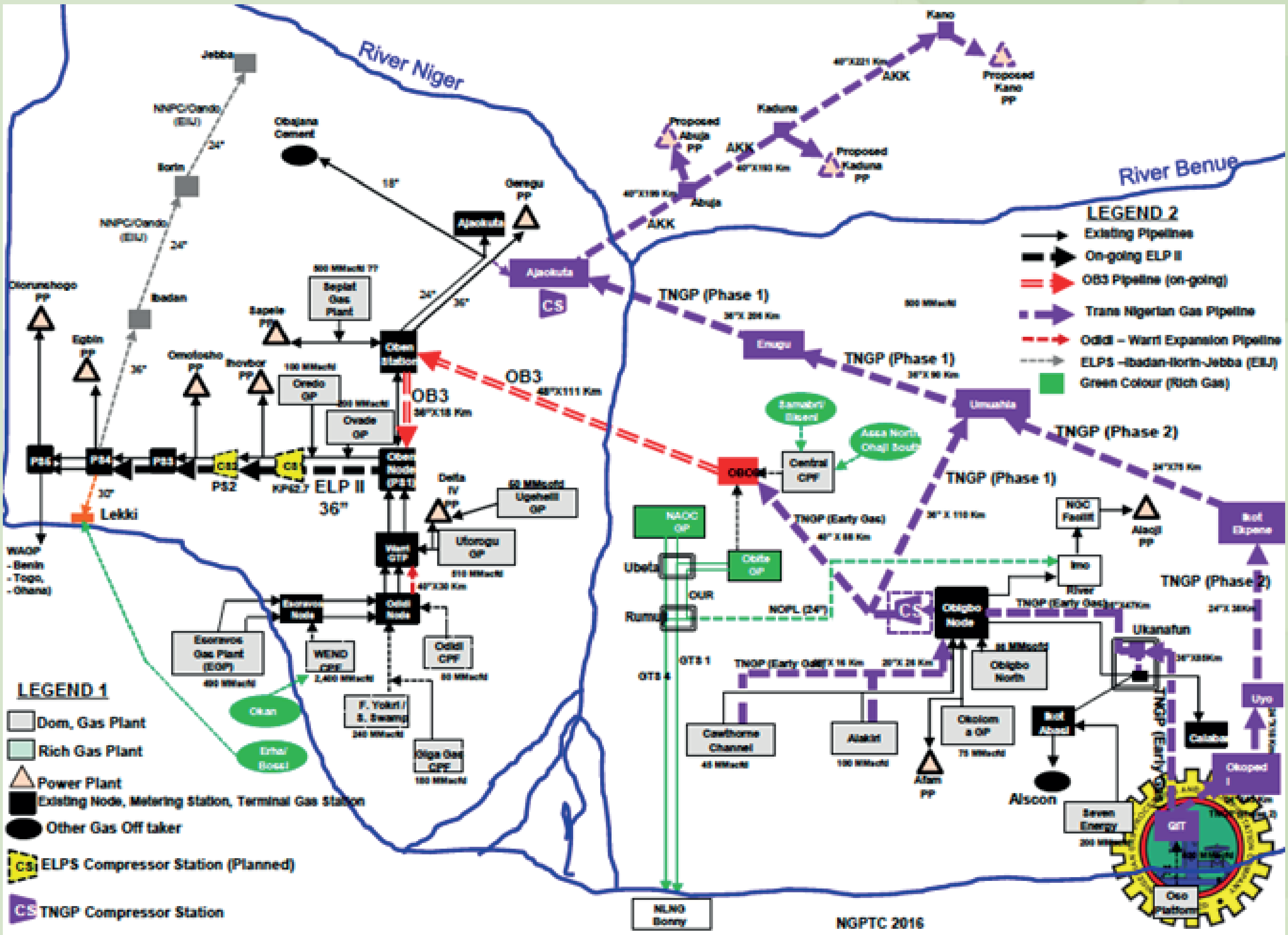

Figure 21: Map of Planned Gas Infrastructure highlighting the ongoing AKK pipeline [62]

4.2.3. Infrastructure for Green Hydrogen Transport and Distribution

The existing road and rail networks in Nigeria that can support the transportation of hydrogen in compressed or liquid form to end-users. Nigeria's ports, such as the Lagos Port Complex and Onne Port, can facilitate the export of green hydrogen and ammonia to international markets. These ports can also handle the import of hydrogen-related equipment and technologies. Industrial hubs like the Lekki Free Trade Zone and Onne Oil and Gas Free Zone could provide infrastructure for hydrogen transportation and utilization in manufacturing and petrochemical industries. The Nigeria Gas has been extended under the West Africa gas pipeline project to Ghana, the Republic of Benin and Togo. In 2022, Nigeria signed a memorandum of understanding with Morocco and other stakeholders (Mauritania and Senegal), for the 7,000 km Nigeria-Morocco Gas Pipeline (NMGP). The project aimed to transport natural gas from Nigeria to Morocco and potentially Europe, is projected to connect 16 West African countries (Figure 22). The project could also facilitate green hydrogen transport from Nigeria to Europe.

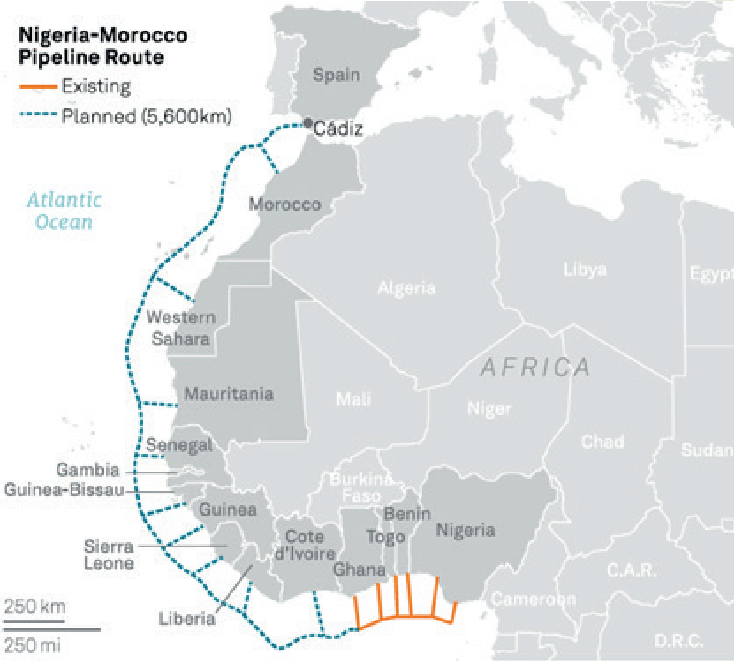

Figure 22: Proposed 5,600 km Nigeria-Morocco Gas pipeline [63]

There is also an African Hydrogen Partnership proposed pipeline infrastructure for gas, oil and chemical products in Africa (Figure 23) under the Green Hydrogen for a European Green Deal - A 2x40 GW Initiative

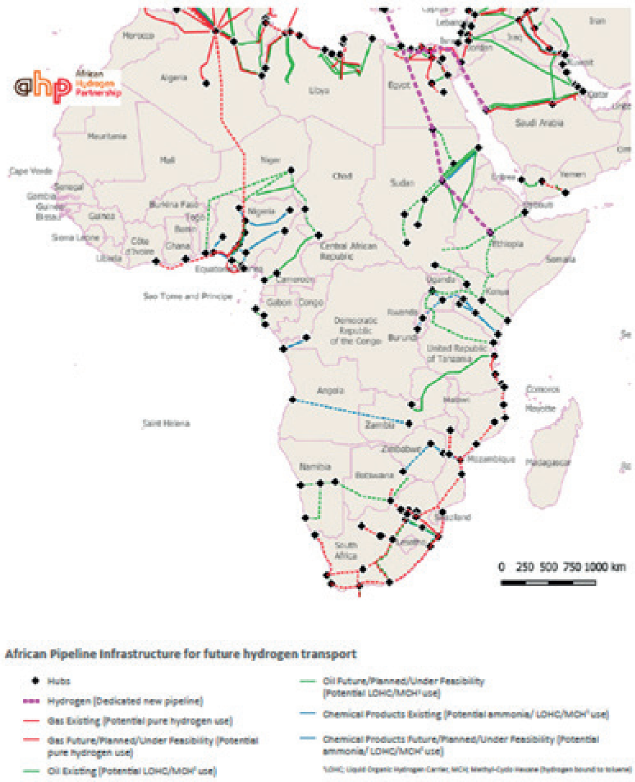

Figure 23: Potential hydrogen infrastructure in Africa with connection to Europe [64]

4.2.5. Ongoing and planned infrastructure

Nigeria is in the early stages of developing infrastructure for green hydrogen and green ammonia. Key ongoing and planned initiatives include:

- o Renewable Energy Projects: Solar farms and wind energy projects are being developed to provide the renewable electricity needed for green hydrogen production. The Nigerian government has set targets to increase renewable energy capacity as part of its Energy Transition Plan.
- o Hydrogen Production Pilot Projects: Pilot projects for green hydrogen production using electrolysis are being explored, particularly in regions with high solar and wind potential. Partnerships with international organizations and private companies are being established to kickstart these initiatives.
- o Ammonia Production Facilities: Existing ammonia production facilities, such as the Indorama Eleme Petrochemicals plant, Dangote Fertiliser Limited and Notore Chemical Industries Plc are being evaluated for conversion to green ammonia production using green hydrogen.
- o Research and Development: Nigerian universities and research institutions are beginning to explore green hydrogen technologies, supported by government and international funding.

4.2.6. Required infrastructure for Green Ammonia

The development of green hydrogen and green ammonia requires a robust and interconnected infrastructure system. Below is a detailed breakdown of the essential infrastructure needed:

- o **Dedicated Renewable Energy Generation Facilities:** Solar Farms, Wind Farms Hydropower and biomass plants are required to generate renewable electricity.
- o **Production Plants:** They are facilities equipped with electrolysers or reformers. They are often co-located with renewable energy sources to minimize energy losses.
- o **Hydrogen Storage Systems:** Hydrogen Storage Systems include Pressurized Tanks for short-term storage of gaseous hydrogen, Cryogenic Storage for liquid hydrogen storage, and Underground Storage, which utilizes salt caverns or depleted gas fields for large-scale hydrogen storage.
- o **Ammonia Synthesis Plants:** Ammonia Synthesis Plants are facilities that convert green hydrogen into green ammonia using the Haber-Bosch process, and can also involve the retrofitting of existing ammonia plants to use green hydrogen instead of fossil fuels.
- o **Transportation Infrastructure:** Transportation Infrastructure for hydrogen and ammonia includes Pipelines, such as dedicated hydrogen pipelines or retrofitted natural gas pipelines, Shipping Terminals, which are port facilities for exporting hydrogen and ammonia, and Specialized Transport Vessels, which are ships designed to transport liquid hydrogen and ammonia safely.
- o **Distribution Networks:** Distribution Networks comprise Hydrogen, trucking, Refuelling Stations, which supply fuel cell vehicles, particularly in urban and industrial areas, and Local Distribution Systems, which provide hydrogen to industries and residential areas.

- **Grid Integration and Power-to-Gas Systems:** Grid Integration and Power-to-Gas Systems involve infrastructure that integrates hydrogen production with the national grid, as well as power-to-gas systems that convert excess renewable electricity into hydrogen.
- **Research and Development Facilities:** Centres for innovation and technology development to advance hydrogen and ammonia production, storage, and utilization technologies.
- Regulatory and Safety Frameworks: Development of policies, standards, and safety protocols to govern the production, storage, and use of hydrogen and ammonia.

5. WATER MANAGEMENT FOR GREEN HYDROGEN PRODUCTION

5. WATER MANAGEMENT FOR GREEN HYDROGEN PRODUCTION

5.1. Water Requirement for Electrolysis

In the context of hydrogen production using water electrolysis, there are three main water mass flows to consider. An ultrapure water stream is required for water splitting, which is partially divided into hydrogen and oxygen. The product streams are then separated by means of a gas-liquid separation and further processed. The liquid phase is fed back into the process cycle and treated further. Stoichiometrically, around 9 kg H2O per kg H2 is required. Depending on the type of electrolyser used, however, more than 10 to 14 kg H2O per kg H2 can be observed in real operation.
A high purity of the water ensures a longer service life of the electrolyser, as various ingredients can affect the electrolyser and its functionality over a longer period of time. (Source Review 2023) The water quality depends on the requirements of the electrolyser used. The electrolyser manufacturers may have slightly different requirements for the various types of electrolysers, but almost all electrolyser manufacturers now follow the standards of the American Society for Testing and Materials (ASTM). The ASTM Type II standard can be used as a guide, as it is currently required by most electrolyser manufacturers. However, the ASTM Type IV standard is often also mentioned as a minimum requirement. A simplified overview of the ASTM water quality standards can be seen in Table 7.

Measurement (Unit)	Type II	Type IV
Resistivity (MΩ-cm)	> 1	> 0.2 (200KΩ)
Conductivity (µS/cm)	< 1	< 5
pH at 25˚C	N/A	5.0 - 8.0
Total Organic Carbon (TOC) ppb or µg/L	< 50	N/A
Sodium (ppb or µg/L)	< 5	< 50
Chloride (ppb or µg/L)	< 5	< 50
Silica (ppb or µg/L)	< 3	N/A

Table 7: Parameters for the ultrapure water quality according to ASTM standards Type II and IV [65]

In order to obtain ultrapure water, the raw water must first be treated. This is done by several consecutive treatment steps, including desalination. A simplified overview can be seen in Figure 24. Depending on the raw water source, the water is first pre-treated. This may include all the steps required to remove suspended solids, as well as softening and the addition of chemicals required for the subsequent process steps. This is followed by a desalination stage, which is referred to as make-up in Figure 24. In this stage, water-soluble substances, especially salts, organic trace substances and fine particles, are removed. Membrane-based desalination processes, such as reverse osmosis and nanofiltration, have made up the majority of desalination processes in recent years, at ~70% (source Jones et al.). However, there are also thermal and hybrid technologies. In order to achieve the required purity, further treatment steps are needed to produce ultrapure water, referred to as the polishing stage in Figure 24. The conventional treatment methods to gain ultrapure water are ion exchangers (IX) or electro-deionization (EDI), which are accompanied by degassing processes and usually UV treatments.

Using these methods, conductivities of <1 µS per cm can be achieved. In this way, ultrapure water is obtained from raw water source as a product stream. However, the whole treatment leads to the production of concentrates/brine, which have to be discharged as waste or wastewater.

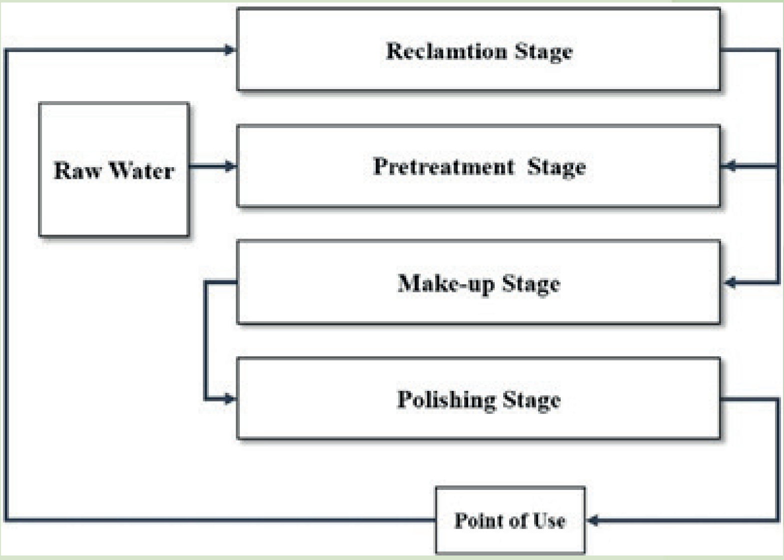

Figure 24: Simplified overview of an ultrapure water production system[66]

In addition to water consumption due to water splitting, water consumption due to cooling should also be considered. Various systems are available for cooling, such as once-through cooling systems, drain cooling systems and circulation cooling systems. In once-through cooling, the cooling medium is passed through and then discharged back into its original source, such as a river, after cooling. Due to the high flow rates, large quantities of water are required for cooling, but these are also returned directly to the cooling water source, water losses can be minimal. It can be planned with 920 to 2,450 kg of cooling water and a heating of the cooling water of 5 to 10 °C.

In the case of discharge cooling, part of the absorbed heat is released into the atmosphere via a cooling tower and the remaining water is discharged. Thus, depending on the proportion of cooling via a cooling tower, the amount of cooling water can be reduced compared to once-through cooling.

In closed-circuit cooling, the majority of the heat is released into the atmosphere or another cooling medium and the cooling water is used several times. This drastically reduces the water requirement to 17 to 40 kg of cooling water per kg of H2 in an open cooling circuit and even less (depending on the system) in a closed cooling circuit. In order to avoid the harmful effects of the resulting concentration of water constituents on the equipment due to corrosion, a small proportion of the water is regularly removed from the cooling circuit (“blow down”) and replaced with fresh water (“make-up” water).

An air-cooling system can be used as an alternative to water cooling. This drastically reduces the water requirement. In order to avoid the negative effects of the resulting increase in the concentration of water constituents, a small proportion of the water is regularly removed from the recirculating cooling water system (“blow-down” water) and replaced with fresh water (“make-up” water).

Air cooling systems are similar to a closed circuit. In a dry cooling tower, the heat is transferred directly to the air, which flows past a series of pipes containing the cooling water. In practice, dry cooling systems use around 95% less water [65]. In addition to the removal of heat, the regional use of waste heat can also be considered, although this must be examined on a project-specific basis.

In the context of water purification and treatment, in addition to ultrapure water as a product stream, wastewater also arises, which must be treated or disposed of. One example of this is the high-saline brine from seawater desalination, if this is considered a raw water source. The quantities of wastewater that arise are heavily dependent on the dimensions of the plant, the raw water source and the water treatment processes.

In the context of hydrogen projects, DECHEMA works with the Water-for-X concept, which provides for integrated water management for green hydrogen plants. This approach attempts to consider all relevant water flows and conditions on different management shells. The aim is to enable water management that ensures a safe water supply with the least possible impact on humans and the environment. An overview of the concept can be seen in Figure 25.

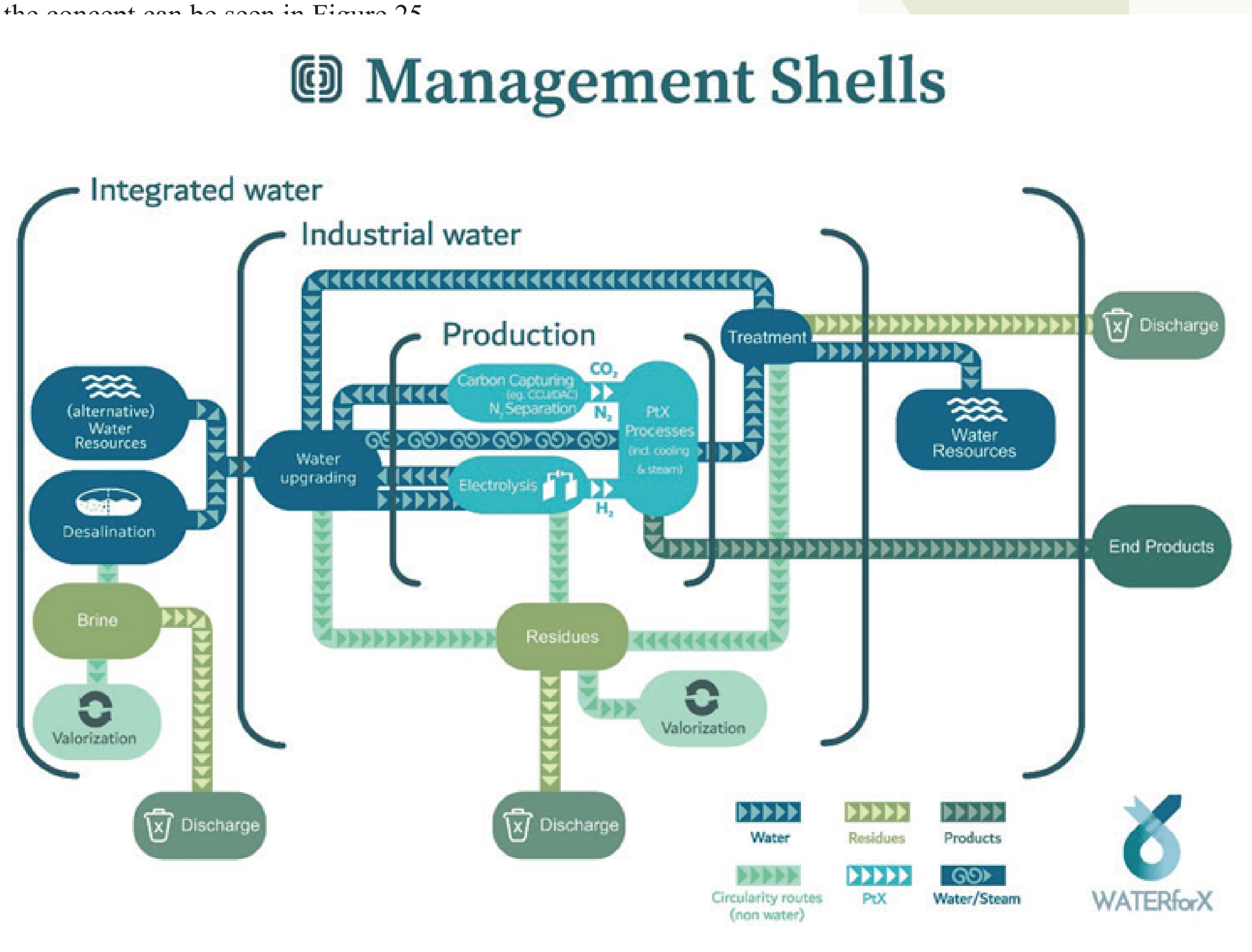

Figure 25: Water-for-X Management Shells [9]

5.2. Potential Water Resources for Green Hydrogen

For the production of hydrogen from water, a raw water source must be available that can provide sufficient water for the production of ultrapure water (UPW) and, if needed, for cooling the electrolyser, without negative consequences for the surrounding ecosystem and its human use. Typical raw water sources are drinking water, groundwater, surface water, brackish water and seawater. The availability of various raw water sources was examined at the national level using literature research.

The raw water sources differ in their regional availability and their composition. Generally, it should be mentioned that the selection of a raw water source depends heavily on the regional location of a plant and should be decided primarily on the basis of availability. If different sources of raw water are available regionally, the selection of the raw water source can result in differences in the required raw water quantity and the required technology for pretreatment. Table 8 provides a rough overview of typical conductivities (an indicator of the salt content in water) and amounts of raw water, approximate by DECHEMA, that are required to produce 1 kg of UPW.

Type of water	Conductivity [µS/cm]	Approximated UPW production factor[kg raw water/kg UPW]
Pure water	0,05	1
Distilled water	2	1
Rainwater	50	1
Tap water	200-1000	1,1 – 1,3
River water / groundwater (typical)	400-800	1,1 – 1,3
River water (brackish)	5000	Highly depending on water
Seawater (coastal)	33000	2 - 3
Seawater (open sea	40000-50000	2 - 3

TTable 8: typical conductivities of raw water sources and approximated factors for UPW production [69]

To gain a first idea about the amount of water available for the green hydrogen economy in Nigeria, a few water resource indicators given by the FAO Aquastat [68] were looked at in comparison to countries with hydrogen ambitions such as Australia, Chile, Morocco, Egypt, and Namibia. Table 9 shows an overview of three important indicators for the year 2021.

Country	Water Stress	Total exploitable water resources [109 m³/year]	Total renewable water resources [109 m³/year]
Australia	4,25	190	492
Chile	8,98	No data	923,06
Egypt	141,17	49,7	57,5
Morocco	50,75	20	29
Namibia	0,86	0,65	39,91
Nigeria	9,67	59,51	286,2

Table 9: water resource indicator data given by FAO Aquastat

From the data shown, it is concluded that Nigeria appears to have an advantage over competing African countries in terms of the availability of water resources and at the same time displays less water stress. Compared to transcontinental competitors, this advantage does not appear to exist. In contrast to the 286.2 billion m³ of total renewable water resources, a total water demand of 5.93 billion m³ per year was estimated for Nigeria in 2021, which is expected to increase to 16.58 billion m³ per year in 2030 [69]. The data presented does not allow any direct conclusions to be drawn about the total available water quantities for a green hydrogen economy. This would require a more detailed study of the water resources at the national level, which should be supported by environmental and social impact analyses (ESIA).

In terms of water stress, it is reported that northern regions of Nigeria experience greater water stress than southern regions, due to growing surface water demands, fewer annual precipitation then in the south and following that declining groundwater levels due to over-abstraction [48].

5.2.1. Drinking water

An analysis of the drinking water supply in Nigeria showed that a comprehensive and safe drinking water supply cannot be assumed. In 2019, only 14% of the population had access to safely managed water services. Although access to basic water services in the year 2018 was higher in urban regions (87.3%) and rural regions (59.7%), these figures do not allow for the conclusion that a safe, comprehensive water supply for a green hydrogen industry is available (Figure 26).

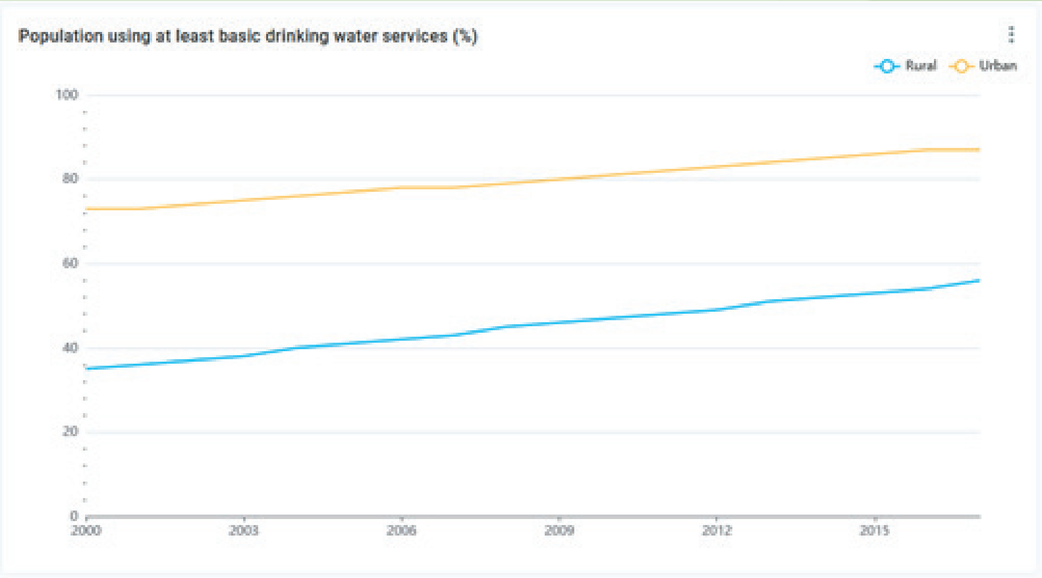

Figure 26: Population using basic drinking water services in Nigeria [71]

No more recent data was found that would suggest a different situation. Drinking water seems to be an option only for plants that are close to large urban areas, that have a sufficient water supply. Based on the data, it was assumed in the context of this project that a drinking water supply for green hydrogen projects is not generally available in Nigeria and that independent water treatment from other raw water sources will need to be carried out.

5.2.2. Groundwater

Groundwater is the most dominant source of water for household supply in Nigeria [70]. The availability of groundwater for use as a raw water source for green hydrogen production is therefore an obvious one. According to FAO Aquastat data, Nigeria has a total renewable groundwater of 87 billion m³ per year in 2021, although this total amount cannot be used exclusively for a green hydrogen economy [68].
A study of the relationship between groundwater and green hydrogen has already been carried out by the H2Atlas project. In the study, a sustainable groundwater yield was determined for the years 2020 and 2050. The results for Nigeria in terms of sustainable groundwater yield can be seen in Table 10.

Groundwater Assessment			
	2020	2050 (Optimistic)	2050 (Pessimistic)
Groundwater sustainable yield (Extreme) [mm/yr]	104.46	108.41	48.05
Groundwater sustainable yield (Medium) [mm/yr]	55.11	48.16	48.05
Groundwater sustainable yield (Conservative) [mm/yr]	8.84	4.29	3.91

Table 10: Results of the Groundwater Assessment for Nigeria in the H2Atlas project [43]

The following methodology was used by H2Atlas to calculate the displayed values:
"For the assessment of current groundwater availability, the long-term (1989-2010) groundwater sustainable yield has been calculated and the average presented here as a representative benchmark for the current situation (2020). The groundwater recharge is obtained from simulations of the Community Land Model [ver. 5] (CLM5) at 3 km spatial resolution, forced by atmospheric data from the third Global Soil Wetness Project (GSWP3). The environmental flow is a certain percentage of the calculated annual recharge, which varies depending on the scenario (i.e., conservative, medium, and extreme scenarios, where 90%, 60%, and 30% of annual recharge is reserved for the environment, respectively). Sectoral water use is obtained from the published literature that takes total water withdrawal for irrigation, domestic use, electricity generation, livestock, mining, and manufacturing into account. "[44]

To obtain the amount of usable water from the sustainable groundwater yield, which was calculated in the H2Atlas Africa project for Nigeria and can be seen in Table 9, the amount of water must be multiplied by the area of Nigeria (923.768 km²). Here, the unit mm per year can be used as L per year. The formula for the conversion can be seen below.Table 10.

$$amount\ of\ usable\ water\left[\frac{m^3}{year}\right] = \frac{Surface\ Area\ Nigeria\ [km^2]\cdot 10^6\left[\frac{m^2}{km^2}\right]\cdot sustainable\ groundwater\ yield\left[\frac{L}{m^2\cdot year}\right]}{1000\ [\frac{L}{m^3}]}$$

The results of the H2Atlas thus indicate usable water quantities of 3,6 billion m³/year (pessimistic scenario 2050 under conservative conditions) to 100,15 billion m³/year (optimistic scenario 2050 under extreme conditions).
Interactive maps can be viewed for the calculated scenarios in the H2Atlas project. As an example, the scenario with medium quantities is shown in Figure 27.

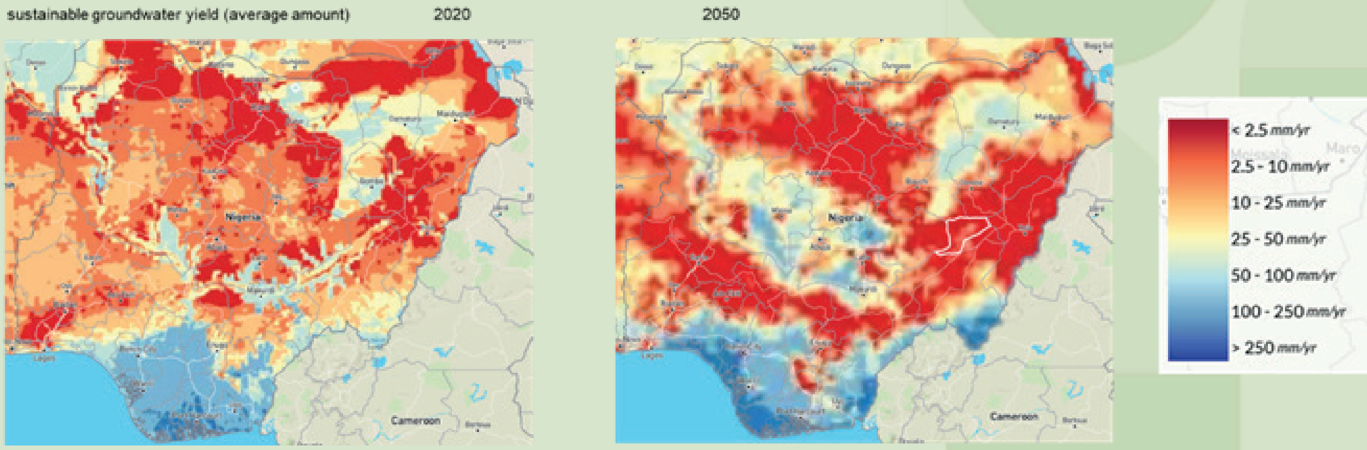

Figure 2627: Groundwater sustainable yield (Medium) for the years 2020 and 2050 conducted in the H2Atlas project [43]

It can be observed that there is increased potential for sustainable groundwater use in southern Nigeria and in the vicinity of the Niger and Benin rivers.
In addition to the groundwater quantities, it is reported that there have been various local contaminations of the groundwater [71], [72], as well as that in the south, saline seawater is entering the groundwater due to its high use, which can lead to local brackish water conditions in the aquifer[73]. When planning a green hydrogen plant with groundwater as raw water, it is advisable to carry out extensive groundwater sampling before determining a location in order to avoid complications for water treatment due to high groundwater contamination.
Within the scope of this study, it is assumed that, based on the information shown, groundwater is a viable raw water resource for the production of green hydrogen in Nigeria. However, potential accessibility is highly depended on local conditions and should be analysed in advance for each specific project.

5.2.3. Surface Water / Hydro-electric Dams

According to FAO Aquastat data, Nigeria has a total renewable surface water of 279.2 billion m³ per year [70]. When considering available raw water sources, surface water in connection with hydroelectric dams was considered in order to utilize the overlap of renewable energy production and direct water availability. A list of identified hydroelectric dams in Nigeria can be seen in Table 11Table 11. Furthermore, additional dams are being planned and constructed, which should further increase capacities.

State	Dam	Energy capacity [MW]	Water Capacity [million m³]	Surface area [ha]	Primary usage
Taraba State	Mambilla Dam	3,050	-	-	Hydro-electric, currently under
Buene State	Markudi Dam	1,650	-	-	Hydro-electric, currently under
Niger State	Kainji Dam	760	15000	130000	Hydro-electric
Niger State	Zungegru, kadina rivers	700	10400	-	Hydro-electric
Niger State	Shiroro Dam	600	-	301200	Hydro-electric power
Niger State	Jebba Dam	578	3600	35000	Hydro-electric power
Oyo State	Ikere gorge Dam	37,5	690	4700	Hydro-electric, water supply

Table 11: Identified hydroelectric dams in Nigeria [76–78]

Figure 28 to Figure 30 show the water levels measured with satellite images of the Kainji, Jebba and Shiroro reservoirs. In addition to annual periodic fluctuations, no decrease in the water volume of the reservoirs has been observed over the last few years.

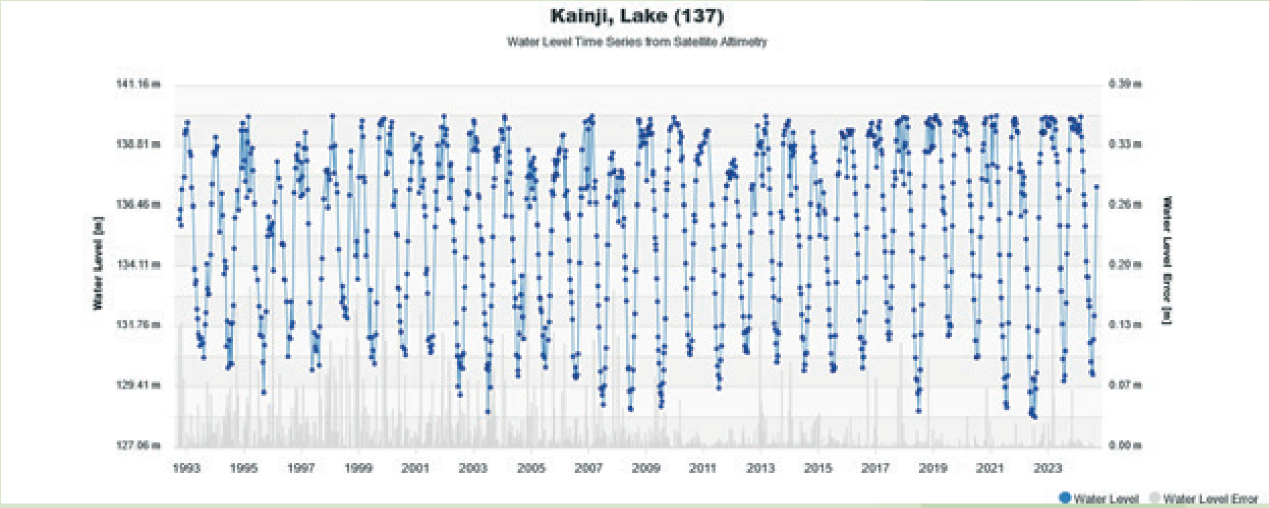

Figure 2728: Water Level Time Series at Kainji Lake measured from Satellite Altimetry[79]

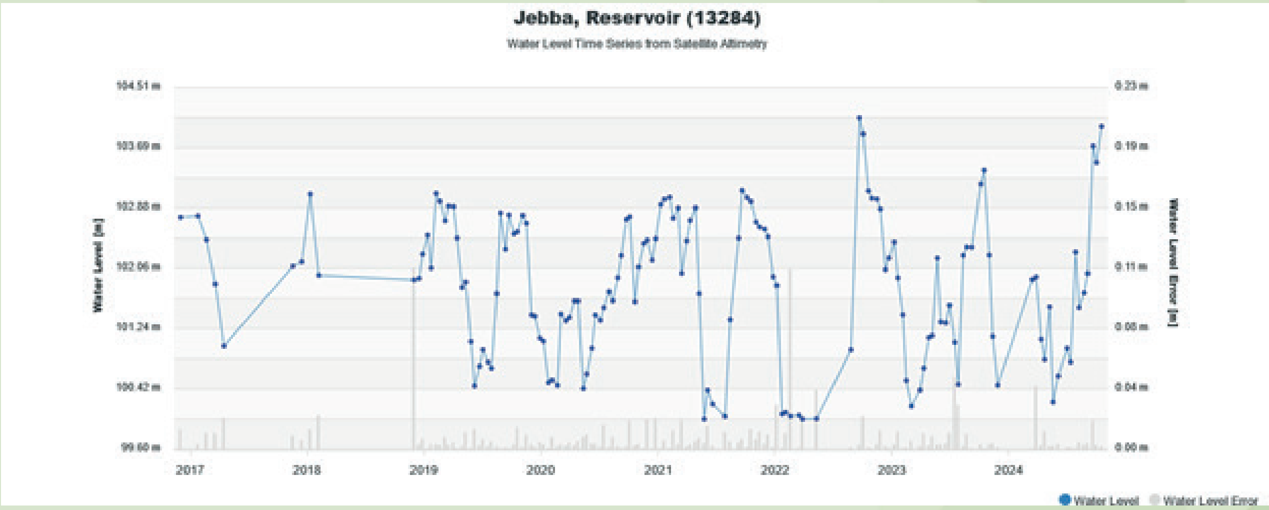

Figure 2829: Water Level Time Series at Jebba Reservoir measured from Satellite Altimetry[80]

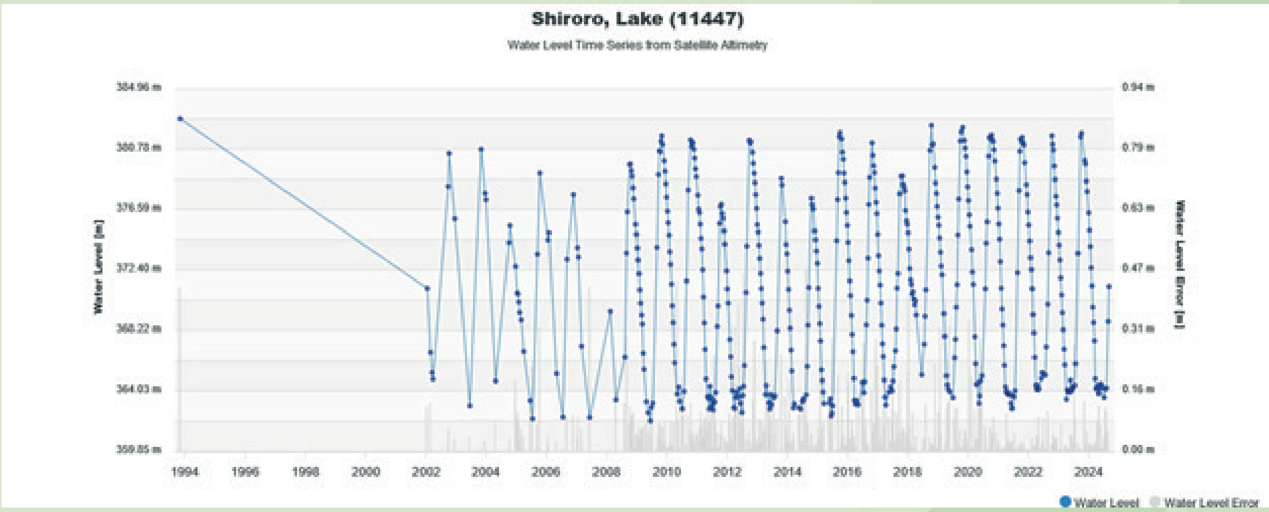

Figure 2930: Water Level Time Series at Shiroro Lake measured from Satellite Altimetry[81]

From the data obtained, it is concluded in the context of this project that the use of surface water behind hydroelectric dams can be a viable source of raw water. However, an analysis should be carried out before planning any plants to determine whether excessive amounts of water withdrawn could have negative consequences for human use and the environment.

5.2.4. Seawater / Brackish Water

The desalination of seawater or brackish water is another option for a water source. This is possible in the south of the country, near the coast. This project assumes that sufficient quantities of water would be available through the use of seawater.

At the time of this report, no major active desalination plant had been identified in Nigeria. However, the Lekki Water Desalination Project has been identified, which currently appears to be in a development phase. The plant, which is to be built in Akodo, Lekki Free Zone, Lagos State, is designed for 200,000 m³ [80]. According to a report by the Global Sovereign Advisory, the project started in 2014 and has not yet been implemented [81].

Most recently, a paper was identified that considered a techno-economic analysis of a 100 million litres per day desalination plant in Lekki and came to the conclusion that a plant would be technically feasible, economically viable, and socio-economically worthwhile. The paper identified CAPEX of 70,820 million Naira and OPEX of 20,492 million Naira per year for such a project [82].

Even though there are currently no desalination plants with larger capacities in Nigeria, it is assumed that seawater can be an option for water supply in Nigeria. Furthermore, this project assumes that sufficient water would be available if seawater were used.

5.3. Potential Usage Conflicts of Water

In order to identify potential usage conflicts, a closer look at the Nigerian water supply is necessary. Nigeria faces significant challenges in ensuring adequate and safe water supply for its population. As of 2022, approximately 80% of Nigerians had access to at least basic drinking water services [83]. However, disparities

exist between urban and rural areas; in 2018, 87.3% of urban households had access to improved water sources, compared to only 59.7% in rural regions [69]. Despite these relatively high coverage figures, water quality remains a pressing concern. In 2019, it was reported that more than half of the basic water sources in Nigeria were contaminated [69]. This contamination can contribute to health issues, with 73% of diarrhoeal and enteric disease burdens associated with poor access to adequate water, sanitation, and hygiene services [84].

Additionally, population growth intensifies pressure on existing water resources. In 2019, approximately 60 million Nigerians lived without access to basic drinking water, a situation attributed to inadequate infrastructure, insufficient investment, and a deficient regulatory environment, according to the World Bank Group [85]. Efforts to address these challenges seem to be made, yet the issue persists. However, achieving sustainable and equitable water access for all Nigerians remains a complex issue requiring coordinated action from government entities, international organizations, and local communities. The production of green hydrogen in Nigeria, which relies on water electrolysis powered by renewable energy, can create several potential use conflicts related to water consumption. Those issues are often more pressing in rural than in urban areas. However, due to its industrial nature and space requirements, green hydrogen plants also tend to be located more in rural areas. Potential usage conflicts may include:

- **Drinking Water Supply**
  As mentioned above, many regions in Nigeria already face water scarcity and inadequate access to clean drinking water. Diverting water for hydrogen production could exacerbate shortages for households.
- **Agricultural Water Use6**Agriculture is a major water consumer in Nigeria, particularly for irrigation. Increased water demand for hydrogen production could compete with farming needs, affecting food security.
- **Industrial Competition**
  Other industries, such as manufacturing, mining, and oil refining, also require significant water resources. Green hydrogen projects could intensify competition, leading to higher costs and resource allocation conflicts.
- **Hydropower Generation**
  Nigeria relies on hydropower for a portion of its electricity supply. Increased water use for elec trolysis could impact reservoir levels, reducing the efficiency of hydropower plants. Here good water management plans and protocols should be developed, if a water from Hydropower dams is planned
- **Ecosystem and Biodiversity Impact**
  Large-scale water extraction for hydrogen production can affect wetlands, rivers, and lakes, disrupting aquatic ecosystems and threatening biodiversity. Environmental Impact Assessments (EIA) for every green hydrogen production plant with focus on the additional effect of water withdrawals can be recommended.
- **Regional Water Stress**
  Northern Nigeria is arid, with limited water resources. Expanding green hydrogen projects in these areas could strain existing water availability and exacerbate desertification risks.
- **Urban vs. Industrial Water Needs**
  Expanding hydrogen production in urban centres could create conflicts between municipal water supply needs and industrial hydrogen plants, particularly in rapidly growing cities.

To mitigate these conflicts, Nigeria would need to adopt sustainable water management practices, prioritize water recycling in green hydrogen production, and develop policies ensuring equitable distribution of water resources

5.4. Water-related Policies

5.4.1. Water-related Policies in Nigeria

As part of the project, important policies, regulations and acts for water use in Nigeria were sought. An overview of the results can be found in Table 12. No regulatory framework for green hydrogen and its derivatives, as well as associated resources and wastes in relation to water, could be identified.

Name	Year	Purpose
National Water Resources Policy	2016	Originally drafted in 2004, the National Water Policy was approved in 2016. The policy establishes that all water is a national asset and defines planning and development through an integrated water resources management framework.
Water Resources Master Plan	2013	Assesses water resources supply and demand from 2010 to 2030 and defines basin development priorities and risks.
National Environmental (Surface and Groundwater Quality Control) Regulations	2011	These regulations provide for quality control of and quality standards and requirements of surface waters and groundwater in Nigeria. They concern the protection of water resources for purposes of various uses including clean water supply, agriculture, aquaculture and aquatic ecosystems. Furthermore, it establishes that discharge permits shall be applied for with the National Environmental Standards and Regulations Enforcement Agency (NESREA) in accordance with the National Environmental (Permitting and Licensing System) Regulations, 2009.
The National Inland Waterways Authority (NIWA) Act	1997	AEstablished NIWA and defines its responsibilities towards river navigability, riverbank stabilization, and dam development.
Water Resources Act	1993	Established the Federal Ministry of Water Resources as the lead institution in charge of water resources development, licensing, planning, and use.
Water Resources Act	1990	Established 12 River Basin Development Agencies (RBDA) that are responsible for developing surface and groundwater resources, prioritizing water use for domestic and agricultural purposes. The act was originally enacted in 1976 but has been revised several times.

Table 12: Key policies, regulations and acts in regards to water[48,70]

A restriction on water use is possible under Section 8 of the Water Resources Act. Relevant provisions can be found in:

(a) the Water Resources Act, and

(b) the Water Resources Master Plan (2013).

a. Water Resources Act

The Minister has the authority to prohibit or regulate any activities on land or water that are likely to affect the quantity or quality of water in any watercourse or groundwater.

b. Water Resources Master Plan: Priority of Water Usage

When planning the development of surface water resources, the following principles apply:

- The highest priority is given to domestic water use, while ensuring that the environment is not degraded.
- The second priority is given to irrigation water use, particularly for food security purposes.

Based on the above-mentioned principles, the following priority order of consumptive water use will generally apply when planning the development of surface water resources:

1. Minimum stream flow requirement
2. Municipal water supply
3. Irrigation water supply
4. Other water uses, including hydropower (if applicable)

For actual operations during extreme events such as droughts or floods, priorities should be determined through stakeholder discussions on a case-by-case basis. This forms part of the overall risk management strategy for water resources.

For plants that commercially produce hydrogen and therefore use water for commercial purposes, it should be noted that, under Sections 9 and 10 of the National Water Resources Policy, a license issued by the responsible Minister is required for such use.

In addition, permits for the discharge of wastewater are issued by the National Environmental Standards and Regulations Enforcement Agency (NESREA) in accordance with the National Environmental (Permitting and Licensing System) Regulations, 2009.

5.4.2. Possible Water-related Policies for Nigeria

In order to promote the production of green hydrogen and ensure water security in Nigeria at the same time, it is advisable to introduce or support the implementation of the following political policies:

Integrated Water Resource Management (IWRM) Policies

- Strengthen Nigeria’s Water Resources Act to ensure green hydrogen projects align with national water priorities.
- Enforce sustainable water abstraction limits for industries, preventing over-extraction and maintaining availability for agriculture, drinking water, and ecosystems.
- Develop water allocation frameworks that prioritize human consumption, food production, and renewable energy needs.

Industrial Water Use & Recycling Regulations

- Mandate water efficiency standards for hydrogen producers, requiring the adoption of advanced water-saving electrolysis technologies.
- Provide incentives for wastewater treatment and recycling in hydrogen production to minimize reliance on freshwater resources.
- Promote the use of brackish water and desalination in green hydrogen projects, supported by comprehensive water monitoring systems.

Environmental & Sustainability Standards

- IImplement Environmental Impact Assessment (EIA) requirements for hydrogen projects, including an evaluation of water stress in the proposed area.
- Introduce mandatory water sustainability reporting for green hydrogen producers to track and manage their water footprint.
- Promote ecosystem conservation policies to protect water bodies and prevent pollution from byproducts of green hydrogen production.
- Strengthen cooperation with transboundary water management bodies to ensure that Nigeria's hydrogen-related water use does not trigger regional disputes (e.g., Lake Chad and the Niger River)
- Establish a task force on green hydrogen and water, involving all relevant ministries and environmental agencies, to balance hydrogen development with water security.
- Develop regional water-use strategies to prevent excessive hydrogen production in water-stressed areas such as northern Nigeria.

Investment & Incentives for Water-Secure Hydrogen

- Provide incentives for companies investing in water-efficient hydrogen production.
- Encourage public-private partnerships to develop water-smart hydrogen infrastructure.

Legal & Institutional Framework Updates

- Amend Nigeria's National Water Policy (2016) to incorporate green hydrogen production into national water planning.
- Update licensing and permitting regulations for industrial water use, ensuring green hydrogen projects meet strict water sustainability criteria.
- Strengthen monitoring and enforcement mechanisms to prevent illegal or excessive water withdrawals and wastewater discharges by green hydrogen producers.

By adopting these policies, Nigeria can build a water-secure green hydrogen industry while safeguarding vital water resources for agriculture, drinking water, and energy production.

It is important to emphasize that the successful implementation of water-related green hydrogen policies can generate significant local socio-economic benefits. The same applies to policies supporting renewable energy, which is also a critical input for green hydrogen production.

DECHEMA's experience in other international projects—such as GreeN-H_2 Namibia—has shown that clear regulations governing water use in green hydrogen development can positively influence the overall perception of the industry. This effect is particularly evident in regions facing high water stress, where water is widely regarded as a sensitive resource.

5.5. Water-related Infrastructure

Producing large amounts of hydrogen requires significant quantities of pure water. Therefore, a sustainable water infrastructure is essential for the future hydrogen economy.

In general, such water infrastructure should include:

- **Water extraction facilities** – Wells, boreholes, river or ocean intake stations will be necessary to have access to needed amounts of raw water for the green hydrogen production via water electrolysis;
- **Pipelines & Water Transport Systems** – Infrastructure to move water efficiently from sources to the green hydrogen production sites is necessary.

Additional infrastructure components can be part of water infrastructure or are necessary for the production of hydrogen e.g., raw water treatment or desalination.

5.5.1. Water Treatment & Recycling Infrastructure

- **Water treatment and desalination plants** – IWhen seawater is used, desalination facilities are required, and raw water must be treated to produce purified water suitable for electrolysis.
- **Wastewater recycling & reuse systems** – Facilities for treating and reusing water from green hydrogen production can help reduce freshwater demand.
- **Brine and wastewater management systems** – SAs desalination produces ultrapure water, proper disposal or repurposing of brine and wastewater is essential to minimize environmental impacts.

5.5.2. Water Storage & Conservation Infrastructure

- **Reservoirs & water storage** – To ensure reliable water availability, particularly in regions prone to drought, storage facilities should be developed.
- **Aquifer recharge & management facilities** – IInfrastructure to support groundwater sustainability and prevent over-extraction is essential.

5.5.3. Monitoring & Regulatory Infrastructure

- **Water quality monitoring laboratories** – To ensure that the water used in electrolysis meets the required purity standards, monitoring is necessary.
- **Regulatory bodies** – Facilities to oversee water allocation, permitting, and enforcement for hydrogen producers are part of this framework.

5.5.4. Emergency & Climate Resilience Infrastructure

- **Flood control & drainage systems** – To protect water treatment and hydrogen plants from flooding and ensure continuous operations.
- **Drought mitigation infrastructure** – Technologies like underground water reserves and artificial recharge systems to store excess water during rainy seasons can be helpful.

By developing these water-related infrastructures, Nigeria can sustainably support a green hydrogen economy while safeguarding water security for agriculture, drinking water, and other industries.

5.6. Potential Hydrogen Production Scenarios in Nigeria

After evaluating potential raw water sources, three hydrogen production scenarios were identified as part of the project to assess how hydrogen production could be integrated with Nigeria's water supply. The three identified scenarios are:

1. Groundwater abstraction combined with photovoltaic (PV) systems for green hydrogen production
2. Surface water use combined with hydropower
3. Seawater desalination combined with wind turbines as a renewable energy source

For the three scenarios, the water treatment is the same in that water for water splitting must be treated/pretreated to a certain water quality and then treated to achieve UPW-quality by means of further treatment processes. The process of UPW treatment is independent of the raw water source.

Another factor that is the same for all scenarios is that the water treatment process produces a pure water stream for hydrogen production and a concentrate/wastewater stream. The wastewater must be discharged or treated. According to the information found, over 80% of industrial effluent is not treated in Nigeria [86]. A location decision could also be made based on whether a wastewater treatment system is nearby to treat the volumes of wastewater. An exception to this is seawater abstraction, which is discussed in the corresponding subchapter.

In principle, it should be noted that water treatment and management should be considered site- and project-specifically. Thus, this work provides general technical considerations of potential treatment processes for the raw water sources, but no design of a treatment path is made according to a standardized scheme.

5.6.1. Determination of Water Requirements for a Green Hydrogen Economy in Different Scenarios

It should be noted that due to the lack of national green hydrogen targets, no comparisons of water demand in relation to current municipal and indigenous water demand can be made.

When talking about water in the context of green hydrogen production, it is also important to distinguish which water quality is meant. When the system is supplied with water from a specific water source, the term raw water is used. Raw water sources can be groundwater, surface water (such as water reserves from dams, for example), seawater or even drinking water from a drinking water network. Raw water usually has a salt content, hardness, organ content or other impurities that could hinder the operation of the green hydrogen plant, and this raw water must subsequently be treated.

The water is then treated for the operation of the system and designated as process water. Process water must achieve different water qualities, depending on its use in the plant.

For the conversion of water into hydrogen in the electrolyser, for example, ultrapure water is required. This can be based on the ASTM Type II standard, which requires a conductivity of <1 µS per cm. This standard is the requirement which most electrolyser manufacturers now set on the market. ASTM Standard Type IV, which requires a conductivity of <5 µS per cm, is often cited as the minimum requirement. These water qualities cannot be achieved using stand-alone desalination processes, such as reverse osmosis or thematic processes, which means that ultrapure water treatment is necessary.

FFor all three scenarios, the water treatment requirements are similar: water intended for electrolysis must first be treated or pretreated to a specific quality and then further processed to achieve ultrapure water (UPW) quality. The UPW treatment process is independent of the raw water source.
Another common factor across all scenarios is that the water treatment process generates two streams: a pure water stream for hydrogen production and a concentrate/wastewater stream. The wastewater must either be treated or properly discharged. According to available information, over 80% of industrial effluent in Nigeria is not treated [86]. Therefore, location decisions could consider the proximity of existing wastewater treatment facilities capable of handling the required volumes. An exception to this is seawater abstraction, which is discussed in the corresponding subchapter.
In principle, it should be noted that water treatment and management must be considered on a site- and project-specific basis. Accordingly, this work provides general technical considerations for potential treatment processes for different raw water sources but does not propose a standardized treatment scheme.

5.6.2. Groundwater Scenario

The analysis of the availability of groundwater showed that regions along the Niger and Benue rivers, as well as the south of the country, appear to have more easily accessible groundwater resources. This is supported by the fact that renewable groundwater resources are strongly related to groundwater recharge, which in turn depends on factors such as precipitation. In recent years, it has been observed that regions in northern Nigeria receive less precipitation and thus have less renewable groundwater than regions in the south of the country.
Compared to surface water and seawater, groundwater is typically the purest raw water source, which suggests that hydrogen production using groundwater as the raw water source also means that less raw water needs to be used than with surface water and seawater.
It has been observed in the literature that the groundwater quality in the country is variable, as groundwater contamination may have occurred in various places [72].
Therefore, before selecting the production site, groundwater sampling should be carried out to define the existing groundwater quality.
For the pre-treatment of groundwater as raw water, it must first be pumped. To ensure that the pumping does not have any negative consequences due to excessive withdrawals, it is recommended that project-specific EIAs be carried out to assess the ecological consequences of the water withdrawal. If large quantities of water are withdrawn, it is recommended that the water be pumped from several wells. This way, different wells can be used at different times and an ecological use can be ensured. The costs for the drilling are location-specific and depend on the depth of the borehole.

The pretreatment of the groundwater depends on the site-specific conditions. Possible technologies and treatment steps are:

- Filtration to remove particulate matter,
- Oxidation to precipitate oxidizable ions such as iron or manganese,
- Coagulation flocculation to remove suspended solids,
- ion exchangers to remove hardness and other salts

This is followed by further water treatment using desalination processes, such as membrane or thermal methods, and subsequent ultrapure water (UPW) treatment using electrodeionization (EDI) or ion exchangers.

Cost estimates for groundwater pre-treatment depend on the quality of the groundwater and should be treated with caution, as the cost of a water treatment system is heavily influenced by the size and complexity of the required treatment.

Depending on the selected treatment processes, wastewater may be generated, including saline concentrates from desalination and, periodically, regenerates from ion exchangers. In addition, sludges from coagulation, flocculation, and filtration processes will also be produced.

5.6.2.1. Potential Water Demand

If Nigeria targets 1 million tons of green hydrogen per year, groundwater abstraction would require:

- Water need for electrolysis: about11 to 14.5 million m^3
- Total industrial water need: about 22 to 28 million m^3

5.6.2.2. Challenges & Risks

- Depletion of aquifers: Excessive groundwater extraction can lead to water table decline
- Salinity issues: Over-extraction can cause saltwater intrusion, affecting freshwater availability.
- Competition with agriculture and households: Many Nigerian farmers depend on groundwater for irrigation. Increased hydrogen production could reduce availability for food production. Also, groundwater wells are a common water source for rural households.

5.6.3. Surface Water Scenario

In this scenario surface water in connection with hydro-electric dams is considered to utilize water as an energy carrier and as a raw water source for hydrogen production. To maximize the use the water withdrawal should take place after the dam in order not to lose any energy potential. The water intake to the plant can be done by direct extraction.

In contrast to groundwater, surface water can contain significant concentrations of organics and nutrients (nitrogen and phosphorus). A variety of different biological processes with or without aeration can be used to remove organic matter and nutrients. The selection of the process is highly dependent on the amount of water to be treated and the existing loads. The sludge generated by the biological treatment must be treated to avoid negative consequences for humans and the environment if the untreated biologically active sludge is disposed of directly.

- The pretreatment of surface water can include the following potential treatment steps: filtration to remove particulate matter,
- Biological treatment with or without aeration to remove organic matter and nutrients,
- Coagulation flocculation to remove suspended solids,
- ion exchangers to remove hardness and other salts
- Membrane processes to remove higher salt concentrations

For groundwater treatment, pretreatment is followed by further processes such as desalination, using membrane or thermal methods, and subsequent ultrapure water (UPW) treatment with electrodeionization (EDI) or ion exchangers.

In Nigeria, there is experience in treating surface water to potable water standards, particularly from dams. An example is the Lower Usuma Dam Water Treatment Plant (LUDWTP) [88].

One advantage of producing hydrogen near a hydroelectric power plant is that river water can be used as cooling water in a once-through system. For larger plants, the volume of water requiring treatment can be reduced, even if the total water circulated in the cooling circuit increases.

5.6.3.1. Potential Water Demand

If Nigeria targets 1 million tons of green hydrogen per year, groundwater abstraction would require:

- Electrolysis water need: around 12 to 15.5 million m^3
- Total industrial water need: around 23 to 29 million m^3

Major sources of surface water for electrolysis could include:

- Niger River
- Benue River
- Hydropower reservoirs
- Lake Chad, even though it might be under stress and is shared with neighbouring countries, which would require good international water management

5.6.3.2. Challenges & Risks

- Seasonal variability: Many Nigerian rivers experience dry season flow reductions, making supply inconsistent.
- Impact on hydropower: Diverting water from dams like Kainji could reduce electricity generation.
- Ecosystem disruption: Reducing river flows could affect fisheries, biodiversity, and downstream communities.

5.6.4. Seawater Scenario

The use of seawater as a raw water source is only an option for producing hydrogen in coastal areas. The treatment of seawater to produce potable water is carried out using desalination processes, which primarily have the aim of reducing the salt concentrations of the seawater. The salt concentration in the Gulf of Guinea, which is the prevailing current along the coast of Nigeria, is ~35g per litre [89].

Various membrane processes, thermal processes and hybrid processes are available for treating seawater. In seawater desalination, the raw water is divided into a water stream with reduced salt concentrations (permeate) and a water stream with increased salt concentrations (concentrate/brine). Reverse osmosis as a membrane-based process is the most commonly used desalination process worldwide [90]. Potential process steps for a desalination plant with reverse osmosis are:

- Pumping station for seawater intake
- Filter for removing particles
- Ion exchanger for softening
- Addition of chemicals to prevent scaling and fouling

- Pumps to build up the required pressures
- Prefiltration with ultrafiltration for the removal of suspended solids
- Reverse osmosis for the removal of salts and other substances in the water, potentially a multi-stage process
- Clean-in-place (CIP) for regular cleaning
- Energy recovery systems.

After seawater desalination, the permeate produced typically requires only ultrapure water (UPW) treatment using electrodeionization (EDI) or ion exchangers.

The costs of seawater desalination depend on the size of the plant and the technologies employed. Operating costs are strongly influenced by prevailing energy prices. Seawater reverse osmosis, for example, requires approximately 3–7 kWh per m^3 to produce potable water [81].

In addition to the permeate, desalination generates a significant amount of concentrate, which varies depending on the technology and operating conditions. Seawater reverse osmosis typically operates at 30–50% rejection, producing roughly 1 to 2 liters of brine per liter of permeate. This brine must be properly disposed of or treated. Options include [91]:

- Surface water discharge
- Sewer discharge
- Deep Well Injection
- Evaporation Ponds
- Land Application
- Further treatment with minimal or zero liquid discharge approach

From the options mentioned, the most commonly used option when considering desalination plants globally is to discharge the brine back into the sea [90]. To avoid negative consequences, an EIA is strongly recommended before deciding on a disposal strategy.

5.6.4.1. Potential Water Requirements

Seawater cannot be used directly for electrolysis due to high salinity; desalination is required. Since seawater typically has the highest amount of salt, the largest amount of raw water is needed to produce 1 kilogram of ultrapure water, in comparison to groundwater and surface water.

- Electrolysis water need: around 29 to 40 million m^3
- Total industrial water need: around 66 to 82.5 million m^3

5.6.4.2. Challenges & Risks

- High energy demand: Desalination is energy-intensive, increasing production costs unless powered by renewable energy (e.g., solar, wind).
- Environmental concerns: Disposal of brine (high-salinity wastewater) can harm marine ecosystems, if managed poorly.
- Infrastructure costs: Seawater desalination requires large-scale investment in coastal water treatment facilities.

5.6.5. Comparison of Scenarios

In general, groundwater should be used cautiously in arid and semi-arid regions. Prioritizing agriculture and drinking water over hydrogen production may be necessary to ensure the local population's water and food security. Surface water can be a viable source for hydrogen in high-rainfall areas but must be carefully managed to prevent ecosystem damage and resource conflicts. Seawater desalination offers a sustainable long-term option, particularly if powered by renewable energy in Nigeria's coastal regions.

Table 13 summarizes the comparison of the different scenarios.

Scenario	Water Requirement (per kg H_2)	Major Risks	Best Locations	Key Mitigation Strategies
Groundwater	22-28 litres	Aquifer depletion, competition with agriculture	Anywhere, if groundwater is available; more suitable option for Northern & Central Nigeria	Strict regulation, brackish water use, water recycling
Surface Water	23-28 litres	Seasonal variability, hydropower impact, transboundary disputes	Niger & Benue Rivers, close to hydropower dams	Sustainable extraction limits, ecosystem protection
Seawater (Desalination)	66-82.5 litres (intake)	High energy use, brine disposal, high costs	Coastal regions (Lagos, Port Harcourt)	Renewable-powered desalination, brine management

Table 13: Comparison of different water sources in Nigeria for hydrogen production

To ensure water security for both the population and industry, Nigeria should:

1. Establish strict water-use regulations for hydrogen producers.
2. Prioritize water-efficient electrolysis and treatment technologies.
3. Promote water recycling and the use of alternative sources (e.g., brackish water or industrial wastewater).
4. Implement regional planning to locate hydrogen production in water-abundant areas

5.7. Costs of Water Treatment for Green Hydrogen

Defining precise CAPEX and OPEX values for Nigeria proved challenging, so general estimates from literature were used as a reference.

It is important to note that costs for water treatment plants vary significantly depending on site conditions and the technologies employed. The values provided below are indicative and should be verified for each specific project.

5.7.1. Groundwater Treatment

Groundwater treatment is typically the most economical option for raw water sources, as pre-purification typically takes place through the soil layers. The treatment processes are also often relatively inexpensive. Higher costs can arise due to contamination and the treatment of aquifers close to salt water. The groundwater extracted here can then have higher salt and contamination levels and be defined as brackish water. This is related to the fact that higher costs are involved when advanced treatment options are required to treat the groundwater.

Values found for CAPEX of groundwater are in the range of 475 to 2.800 € per m³ and day and OPEX can range from 0,05€ - 0,63€ per m³ [92].

Key cost drivers could be different Filtration treatments e.g., sand or activated carbon, chemical dosing (iron/manganese removal, disinfection) and membrane-based processes, if required for salinity, hardness, or contaminations.

“The costs for the drilling are location-specific and depend on the depth of the borehole. As a rough estimate, costs from the company Borehole Nigeria could be found [93]:

- 128 to 512 Euro for 20 to 50 meter depth
- 512 to 960 Euro for 50 to 100 meter depth
- 960 to 2,240 Euro for 100 to 200 meter depth

Cost estimates for groundwater pre-treatment depend on the quality of the groundwater. Borehole Nigeria provides indicative costs of €64–€320 for pumps and storage of pumped groundwater, €64–€640 for a basic water treatment system, and €96–€1,280 for advanced water treatment systems [94]. However, these figures should be treated with caution, as the total cost of a water treatment system is highly dependent on the size and complexity of the required treatment.

5.7.2. Surface Water Treatment

Surface water treatment is generally somewhat more expensive than groundwater treatment, although groundwater treatment costs can serve as a rough reference. This is primarily because surface water contains higher levels of organic matter and sediment, which are typically filtered out naturally during groundwater transport through the soil. Direct CAPEX and OPEX values specific to Nigeria could not be identified during this research.

A comparative study from Turkey examined Drinking Water Treatment Plants and illustrated a typical basic process for surface water treatment. The study reported CAPEX for the observed plants in the range of €100–€320 per m³·d, with average OPEX between €0.10 and €0.18 per m³, depending on plant size [95].

As with groundwater, these values may be higher if advanced treatment options are required. Based on DECHEMA’s experience, CAPEX could range from €100 to €1,500 per m³·d, and OPEX could range from €0.10 to €1 per m³.

5.7.3. Seawater Desalination

There is a range of technologies available for desalination of seawater:

- Reverse osmosis (RO)
- Thermal distillation (TD)
- Multi-stage flash distillation (MSF)
- Multiple-effect distillation (MED)

Costs for treatment of seawater are heavily dependent on the desalination technology and its energy consumption (e.g., 3-6 kWh/m³ for RO, >10 kWh/m³ for TD), as presented in Table 14. Also, the chemical pretreatment and post-treatment and membrane replacement can affect costs, as well as high maintenance costs for thermal systems.

Cost	MSF	MED	RO
Capital investment cost	1,600 – 2,750	1,600 – 2,600	1,200 – 2,400
Operational Cost	0.62 – 1.20	0.64 – 0.91	0.55 – 0.84
Total annualized cost	0.80 – 1.52	1.15 – 1.51	1.01 – 1.29

*Table 14: Typical costs of conventional seawater desalination [€/(m³*d)][96]*

5.7.4. Ultrapure Water Treatment

In addition to all the water treatment processes, the treated raw water is treated to produce UPW, which has the required quality for water electrolysis. Ion exchanger (IX) systems and electrodeionization systems (EDI) (sometimes with upstream RO) are the main systems available on the market.

Barros dos Santos et al. [97] showed CAPEX of 1,041.47 € per m³ and d. According to confidential information, CAPEX for EDI systems may amount to around 1,500€ per m³ and d. Marek's comparative study showed that CAPEX differs from manufacturer to manufacturer [98], but that similarly high CAPEX can occur across technologies.

Marek published OPEX of 2.57 to 3.11 € per m³ for IX and 2.31 € per m³ for an RO-EDI system in a system comparison in 2021 [98]. It should be mentioned that in the same publication, Marek also showed significantly lower OPEX (0.24 to 0.35 € per m³) with a different calculation.

Barros dos Santos et al. also showed OPEX for an RO-EDI of 0.54 € per m³ [97]. However, the low OPEX is not consistent with DECHEMA's confidential sources. There, the OPEX was mostly between 1 and 3 € per m³, with most of the information being around 2 € per m³. The main cost-driving factors for ion exchangers are the chemical costs for cleaning the exchange resins and replacing the resins themselves when they no longer have sufficient purification performance, and for EDI systems it is primarily the high energy consumption. It is recommended to calculate with 2 € per m³.

5.7.5. Comparison Summary

As shown in Table 15, CAPEX and OPEX for water from different sources vary widely. Examining OPEX indicates that water treatment is not a major economic factor compared to green hydrogen production costs. Using the highest values, the costs would amount to €4.20 per m³ of ultrapure water, although lower OPEX are more likely. In the worst-case scenario of 82.5 liters per kg H_2 (seawater, Table 12), this translates to approximately €0.3465 per kg H_2. However, actual costs are likely to be much lower and will be case-specific for each green hydrogen plant.

Water Source	CAPEX (€ per m³/day)	OPEX (€ per m³)	Major Cost Factors
Groundwater	500 – 2,000	0.05 – 0.50	Filtration, chemical dosing
Surface Water	100 – 1,500	0.10 – 1.00	Filtration, coagulation, disinfection
Seawater	1,200 – 2,750	0.55 – 1.20	RO/TD, high energy costs, chemical pre- and posttreatment
Ultrapure Water	1,000 – 1,500	0.35 – 3.00	Chemicals and resin exchange for IX and energy consumption for EDI

Table 15: CAPEX and OPEX estimates based on literature and DECHEMA experience

Even these worst-case considerations leave OPEX in the single-digit percentage range compared to optimistic green hydrogen production costs presented by different institutions, which typically lie about 3 € per kg H2.

With groundwater or surface water at around 0.1 € per m³ and only ultrapure water treatment steps required, this would result in 2.1 € per m³ for an estimated 10 litres per kg H2 and only 0.1 € per m³ (utilities) for 12 litres per kg H2. This would result in costs of 0.0222 € per kg H2.

Economic analyses indicate that CAPEX for water treatment can account for up to 5% of the levelized cost of hydrogen, while OPEX ranges from 1–2% (up to 5% for seawater desalination using reverse osmosis) [99].

From a purely economic perspective, treating groundwater and surface water is generally more favorable than seawater. However, the choice of raw water source should also consider water availability and potential ecological impacts. In coastal regions, seawater may be the preferred option.

To mitigate potential conflicts, Nigeria should adopt sustainable water management practices, prioritize water recycling in green hydrogen production, and develop policies to ensure equitable distribution of water resources.

Although there are currently no large-capacity desalination plants in Nigeria, seawater is considered a viable water supply option, and this project assumes sufficient water availability if seawater is used.

From a purely economic perspective, treating groundwater and surface water is generally more favorable than seawater. However, the choice of raw water source should also consider water availability and potential ecological impacts. In coastal regions, seawater may be the preferred option.

6. Ammonia and fertilizer production-general overview

6. Ammonia and fertilizer production-general overview

6.1. Ammonia and Fertiliser Production in General

Ammonia (NH_3) production occurs via the well-established and mature Haber-Bosch process, in which gaseous hydrogen (H_2) and nitrogen (N_2) are chemically combined to form NH_3. The produced ammonia can be classified based on the hydrogen source used in the process and the associated carbon emissions, resulting in the common categories of grey, blue, and green ammonia.

Grey ammonia is fossil-based NH_3, where hydrogen is obtained from natural gas via steam methane reforming (SMR), leading to high carbon dioxide (CO_2) emissions. The nitrogen required for ammonia synthesis is sourced from air injected directly into the reformer. About 85 % of the world ammonia production is based on steam reforming concepts [100]. Blue ammonia is also produced from fossil-based H_2 via SMR, but a carbon capture technology is integrated into the process to retain most of the CO_2. Green ammonia is synthesised using both energy and hydrogen derived from renewable electricity, leading to zero emissions. In the case of nitrogen, since SMR is not implemented here, it is extracted from the air using an air separation unit (ASU), which separates nitrogen from other gases to ensure a pure N_2 supply for ammonia production.

At the core of the process, ammonia synthesis takes place in the Haber-Bosch reactor at a temperature range of 350 – 500 °C, a pressure of 150 – 250 bar, and in the presence of an iron-based catalyst. Approximately 178 kg of hydrogen and 823 kg of nitrogen are required to synthesise 1 ton of ammonia, with conversion rates typically falling between 25 % and 35 %. After the reaction, the output stream is cooled, causing NH_3 to condense. The condensed ammonia is then separated from the unreacted gas, which is subsequently returned to the reactor [101, 102, 103]. The storage and transport of ammonia is typically carried out in its liquid form. This can be done either at a temperature of -33 °C and normal pressure, or at ambient temperature and 8 bar pressure [104].

Ammonia is one of the most widely produced chemicals, primarily used in the agricultural sector. Approximately 75 – 90 % of all synthesised ammonia is utilised in fertiliser production, with an estimated 50 % of the world's food supply dependent on ammonia-based fertilisers [105]. These fertilisers are differentiated according to the type of plant nutrients they contain, such as nitrogen (N) or phosphorus (P).

N-based fertilisers can be obtained by the chemical reaction of ammonia with CO2 or inorganic acids, such as nitric acid or sulfuric acid, resulting in products like urea, ammonium nitrate (AN), and ammonium sulphate (GAS), respectively. Ammonia is commonly used to produce urea, a widely utilised fertiliser. It is produced in integrated chemical plants, in which steam methane reformers (SMR) provide H2 for Haber-Bosch and CO2 for the following urea production [103], [106], [107].

In the field of P-based fertilisers, ammonia is mixed with phosphoric acid to produce a variety of phosphate products, including monoammonium phosphate (MAP) and diammonium phosphate (DAP).

Additionally, potassium (K) is an essential nutrient required for plant growth and development. Various K-based fertilisers are available, such as potassium chloride and potassium nitrate [106]. While these compounds are not typically synthesized via ammonia-based routes, they are crucial components in the production of commercially available NPK bulk blends.

These blended NPK fertilisers consist of a physical mixture of straight N-, P-, and K-based fertilisers, combined in different proportions to provide plants with the proper nutrition for optimal growth. In addition to bulk blends, NPK complex fertilisers are also commercially available. These fertilisers are chemically synthesized, ensuring that all macronutrients (N, P, and K) are chemically bonded and evenly integrated into each granule [106]. NPK complex fertilisers offer the advantage of even nutrient distribution across fields and consistent crop nutrition, while bulk blends are often more cost-effective and provide greater flexibility by adapting to specific soil conditions [108].
Figure 34 presents a schematic overview of the current standard ammonia-based fertiliser production, focusing on the production of NPK blends. After its production at the integrated SMR and Haber-Bosch unit, grey ammonia is subsequently transformed into an intermediate nitrogen-rich product, which is further used in the production of NPK blends.

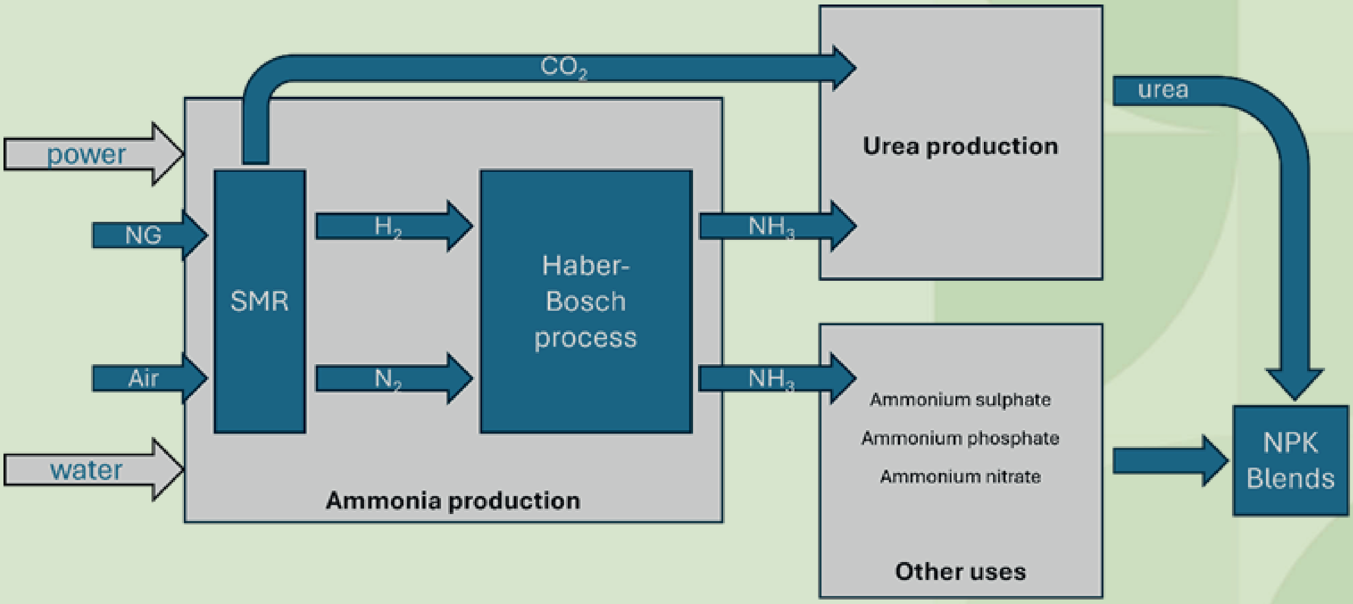

Figure 34: Schematic overview of current ammonia-based fertilizer production pathways. Urea can be part of NPK blends. NG: natural gas. Source: DECHEMA (own figure).

Figure 35 presents the alternative green route based on electrolytically produced hydrogen. The SMR units and natural gas feedstock are eliminated from the process, leading to the production of carbon-free ammonia. In the future, green fertilisers based on green hydrogen may provide an alternative to fossil-based fertilisers. However, as the commonly used urea contains carbon, this route may not be available without alternative climate-neutral carbon sources on a short- to mid-term time scale.

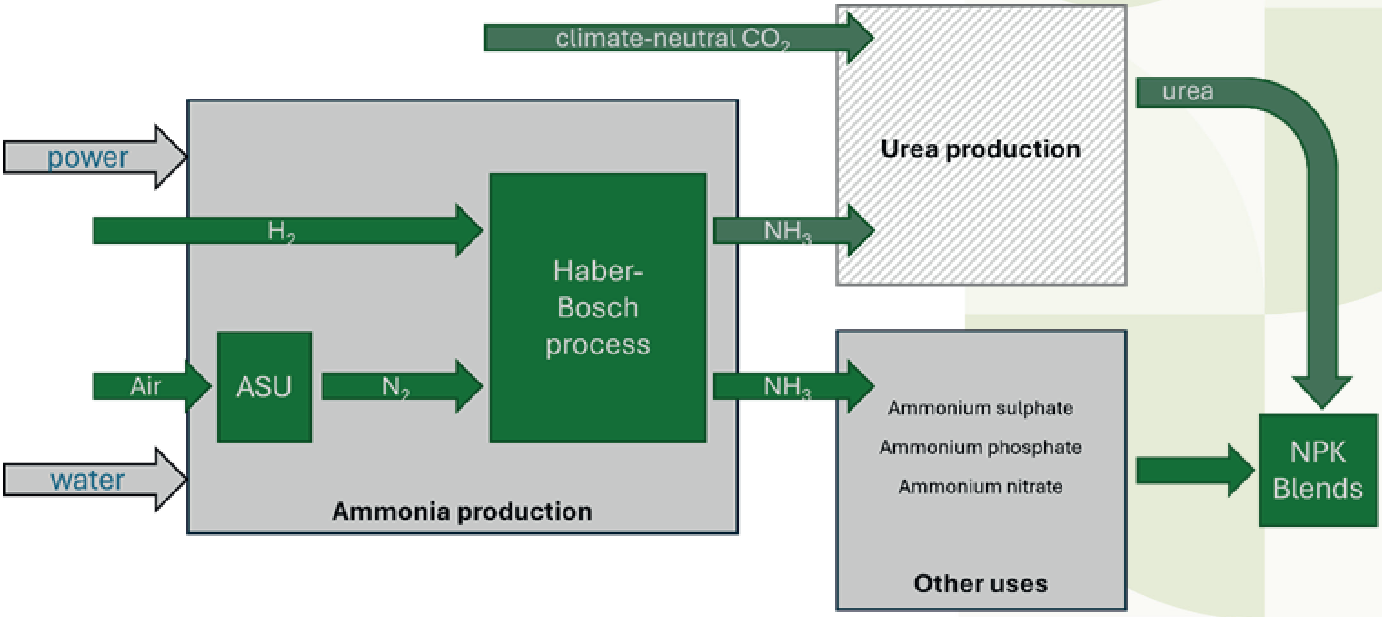

Figure 35: Schematic overview of potential green ammonia-based fertilizer production pathways. Green urea and green urea-based fertilizers require a climate-neutral carbon source. Source: DECHEMA (own figure)..

The global production of urea is increasing and has reached 196 million tons in 2023 [109]. 55 % of ammonia are used for the production of urea on a global scale [110]. Therefore, its precursor ammonia is also increasingly produced with about 240 million tons in 2023 [111] and production volumes are expected to grow by about 1.5 % per year [109]. However, most investments for the next years are based on fossil fuels and green ammonia will likely remain a niche product for a while. The International Fertiliser Association expects about 1 % of global ammonia capacity (3.4 million tons) to be green by 2028 and capacities of up to 146 million tons later on [109]

6.2. Ammonia and Fertiliser Production in Nigeria

6.2.1. Production and Consumption of Fertilisers in Nigeria

The fertiliser industry in Nigeria is primarily focused on urea production from grey ammonia. Three key players dominate the sector, accounting for a total annual urea production capacity of 6.5 million tons. Notore Chemical Industries Plc, active since 2009, has a production capacity of 550,000 tons of urea at its facility. Indorama Eleme Fertiliser & Chemicals Limited operates a complex comprising two production plants, with a combined urea production capacity of 2.8 million tons. The first plant was commissioned in 2016, and the second in 2021.

The largest and most recently commissioned urea plant belongs to Dangote Fertiliser Limited, with an annual capacity of 3 million tons, operating since 2022 [112], [113], [114]. Urea production in Nigeria increased remarkably since the commissioning of the Indorama and Dangote facilities between 2016 and 2022, resulting in current production levels exceeding domestic demand. As a result, large quantities of urea are now being exported, particularly to markets such as Brazil, starting in 2021 [115].
Despite the rapid increase in urea production over the past decade, total production by 2023 still reached only about 60 % of the country's combined capacity of 6.5 million tons. The fact that actual production does not

yet reflect full installed capacity is partly due to issues with natural gas supply [60]. Additionally, newly commissioned plants (such as the Dangote facility) often require a few years to optimize operations before reaching full capacity. Nevertheless, this suggests that urea production will continue to increase in the coming years. Due to the carbon demand of urea, existing facilities would likely synthesise blue ammonia with carbon capture technologies instead of overhauling such a highly integrated facility to switch to green ammonia. This approach allows for a more feasible and cost-effective adaptation to cleaner ammonia production.
Today, the local market is largely dominated by urea and NPK fertilisers. Approximately 630,600 tons of NPK fertilisers are blended annually in the country, with 90 % of them intended for local use. The raw materials used in this process include urea, ammonium sulphate (GAS), diammonium phosphate (DAP), and potassium chloride (also called muriate of potash (MOP)) [60]. With the exception of urea, these NPK precursors are imported [116] and then combined into different fertilisers at NPK blending facilities in Nigeria. This means that all locally produced ammonia intended for fertilisers is entirely converted into urea. Since this imported ammonia-based feedstock for NPK compounds (GAS and DAP) is not yet locally manufactured, it could potentially be produced from green ammonia in the future within the country.

Figure 36 provides an overview of the Nigerian urea market over the past decades, showing trends in total urea production as well as the quantities allocated for local consumption and export [115], [117], [118], [119]. Fertiliser production and consumption in Nigeria have significantly increased in the last two decades. Between 2000 and 2023, urea consumption alone increased by 500 %. As can be observed, local urea production began to increase significantly from 2009, following the start of operations at Dangote's facility. Before this period, fertiliser supply depended mostly on imports of urea and other NPK precursors [118]. Nigeria currently produces enough urea to meet domestic demand and has emerged as a growing player in the global urea market. In 2017, the country accounted for just around 1 % of global urea exports, but this share rose to 3 % in 2021 and further to 8 % by 2023, highlighting a rapid increase in export capacity [119].

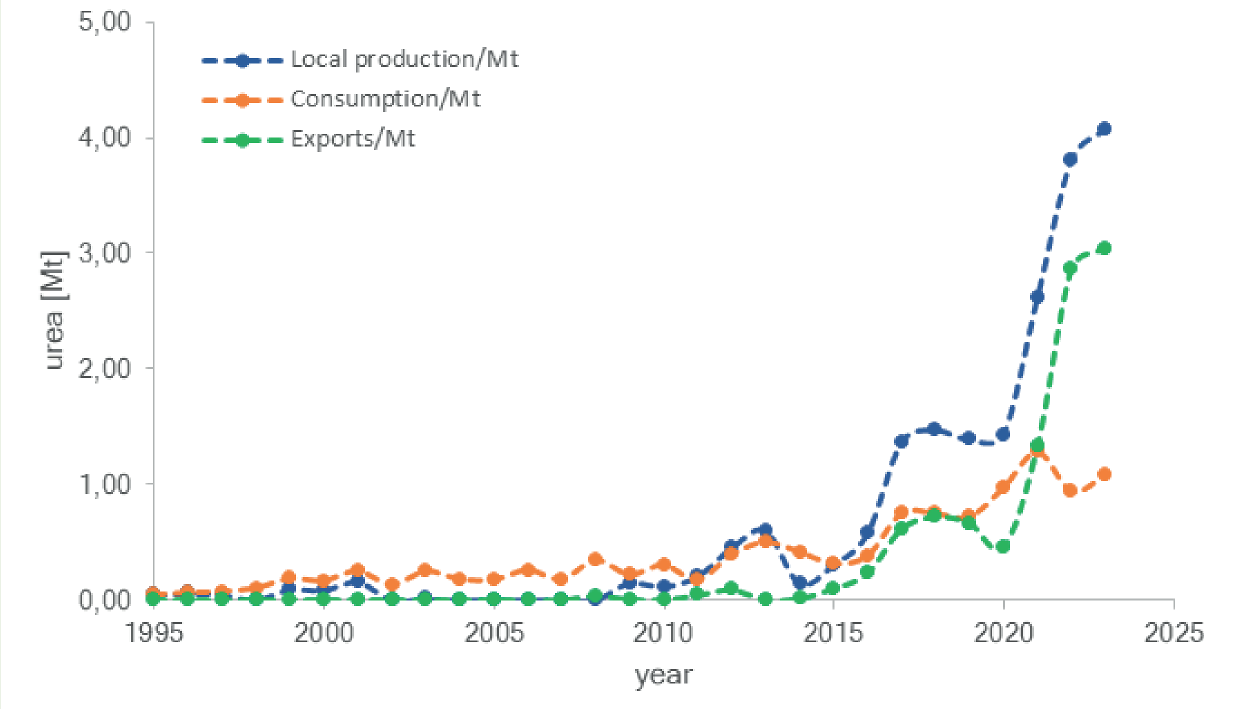

Figure 36: Overview of Nigeria's urea production, consumption, and exports from 1995 to 2023 [60], [116], [117]

In 2023, approximately 4 million tons of urea were produced, with about 3 million tons exported [116], [117]. Thus, according to the Fertiliser Technical Working Group (FTWG) and Africa Fertiliser [117], the apparent consumption of urea in Nigeria is around 1 million tons per year. For instance, 1,082,467 tons of urea were used in 2023. In the same year, the apparent consumption of NPK components did not exceed 560,000 tons [117].

6.2.2. Scenarios for Green Ammonia Production in Nigeria

In general, a continuation of the current trend in the use and production of fertilisers is likely. We therefore assume a rising production of fertilisers in Nigeria over the next decades. However, applications for green ammonia may be limited due to the large-scale production of urea-based fertilisers.

This is supported by the fact that around 70 % of the country's total urea production capacity has been commissioned since 2021 and is based on natural gas, likely using steam methane reforming (SMR) technology. Since these newly built plants are still in the process of depreciation and considering that the SMR unit alone may account for approximately 60 % of the capital expenditure [120], it is unlikely that they would be switched to green ammonia at its assumed high price tag. This makes a transition to urea production via green ammonia not economically feasible in the short term. Carbon capture technologies may offer a more economically feasible short- to mid-term solution to reduce CO2 emissions into the atmosphere for integrated ammonia-urea plants.

6.2.2.1. Scenarios from Literature

According to the scenarios presented by H2 Diplo in their synthesis report [121], three approaches for deploying green ammonia in Nigeria were proposed: the ambitious, the base, and the conservative scenario. Both the ambitious and base scenarios foresee full ammonia production based on green hydrogen by 2060. Considering green ammonia for fertiliser production, the base scenario proposes a gradual adaptation of existing fossil-based urea facilities, targeting a green ammonia production share of 4 % by 2030, 43 % by 2040, and 100 % by 2060. In the ambitious scenario, the transition is accelerated, with new production plants established and existing facilities converted to green ammonia, aiming for a 10 % share by 2030, 70 % by 2040, and 100 % by 2060. In contrast to those scenarios, the conservative scenario outlines a slower deployment in the country, with renewable electrolysis-based production increasing from 0 % in 2030 to 20 % by 2040 and 60 % by 2060 [121].

Therefore, achieving full green ammonia production for fertilisers by 2060, as envisioned in both the base and ambitious scenarios, would likely depend on the effective adaptation of existing grey ammonia facilities to use of green hydrogen. However, given Nigeria's current fossil-based production landscape, with a large and relatively modern capacity operating at less than 70 %, these scenarios may be overly optimistic, particularly in the short to medium term.

However, the conservative scenario seems to offer a more realistic perspective and has therefore been considered in the analysis. In this scenario, existing grey ammonia-based facilities are assumed to continue operating under current technical conditions, while new production plants using the Haber-Bosch process with green hydrogen as feedstock are gradually developed. Consequently, only the newly built facilities would contribute to achieving the green ammonia production shares of 60 % by 2060. For this reason, new ammonia production values based on historic growth trends [101], [110], [111] and export potential [60], [119] and H2 Diplo's green ammonia percentages [121] were calculated in our 'H2 Diplo' scenario.

Table 16 presents the projected total ammonia production under the ‘H2 Diplo’ scenario. Existing grey ammonia facilities are assumed to remain operational, reaching approximately 90 % of total production capacity by 2040, after which their output is expected to remain constant (no expansion of the current urea industry is considered in this scenario). In parallel, new green ammonia facilities are operating by 2040 and continue expanding through 2060 to meet the green ammonia targets. Local ammonia demand was forecast based on the trends shown in Figure 36. As a result, any additional ammonia production, particularly from green sources, is expected to significantly impact export volumes. These exports could occur as pure ammonia or, as is currently the case, in the form of urea.

Year	NH3 production [Mt]			Local NH3 demand [Mt]	NH3 Exports [Mt]
	Grey	Green	Total		
2023	2,3	0,0	2,3	0,6	1,7
2030	2,8	0,0	2,8	0,7	2,1
2040	3,2	0,8	4,0	1,0	3,0
2050	3,2	2,1	5,3	1,3	4,0
2060	3,2	4,8	7,9	1,5	6,4

Table 16: Projected ammonia production for fertilisers in the ‘H2 Diplo’ scenario in million tons [Mt].

The global urea market reported a total export volume of 37 million tons in 2023, with Nigeria contributing 8.2 % of that amount. Based on historical trends, total global urea exports are projected to reach 51 million tons by 2060 [119]. Considering these market trends and the values presented in Table 1, Nigeria’s share of global urea exports is expected to increase from 11 % by 2040 to 15 % by 2050, and up to 22 % by 2060.

Under the assumptions of the ‘H2 Diplo’ scenario, alternative development pathways could also be considered. These might involve a slower expansion of new green ammonia plants, while existing grey ammonia facilities are gradually adapted to use green hydrogen in an economically feasible manner. In this way, the green ammonia share would be met partly through newly built plants and partly through retrofitted existing installations. Due to the scope of this work, such alternatives are not presented here.

The ‘H2 Diplo’ scenario would still require the rapid deployment of very large green ammonia production facilities. While technically feasible, achieving 5 Mt of green ammonia production per year by 2060 could pose additional challenges. These challenges derive from the need to transform the country's energy infrastructure, secure significant investments and develop a supportive policy and regulatory framework. For this reason, alternative scenarios for green ammonia production in Nigeria are presented in the next section, aiming to explore more gradual and adaptable pathways.

6.2.2.2. Scenarios developed in this Study

A first “best guess” scenario is proposed, assuming that green hydrogen will not be integrated into existing urea-producing fertilizer plants over the next decades. Under this scenario, existing grey ammonia facilities are expected to continue operating under current technical conditions, while newly built plants would account for the entire share of green ammonia production. The expansion of new green ammonia plants is expected to follow a gradual path, with additional production contributing to increased export volumes.

While the “best guess” scenario outlines a pathway for large-scale green ammonia production in Nigeria, a second approach—the “local NPK” scenario—focuses on smaller-scale green ammonia production. This scenario considers Nigeria’s domestic needs and offers a more practical option for developing a green ammonia value chain. Currently imported ammonia-based feedstocks for NPK blends (e.g., GAS and DAP) could be locally produced from domestic green ammonia. Existing urea plants, with limited potential for rapid conversion to green ammonia, would continue using natural gas, while all new green ammonia would be dedicated to NPK precursor production. Green ammonia, GAS, and DAP would be produced in newly built facilities, with NPK fertilizers blended at existing sites.

As in the “best guess” scenario, grey fertilizer production would not transition to green ammonia, since a shift to blue ammonia may be more economically attractive after full depreciation.

Table 17 and Figure 37 present the varying shares of green ammonia in Nigeria’s total ammonia production under the three scenarios described.

Year	Local NPK	Best guess	H2 Diplo [121]
2030	0.5 %	2 %	0 %
2040	2 %	10 %	20 %
2050	5 %	20 %	40 %
2060	8 %	50 %	60 %

Table 17: Percentage of green ammonia production in Nigeria over time in the different scenarios

As illustrated in Figure 37, the “best guess” scenario envisions a gradual integration of green ammonia facilities in Nigeria. The initial slow pace reflects the country’s adaptation to new technologies, particularly hydrogen production via electrolysis powered by renewable electricity. Green hydrogen production and subsequent ammonia synthesis are still at an early stage, with relatively high associated costs. However, as the technology matures, capital expenditures decrease, and renewable energy infrastructure expands, a significant acceleration in green ammonia production is expected. This trajectory suggests a quasi-exponential growth pattern, reflecting typical technology adoption.

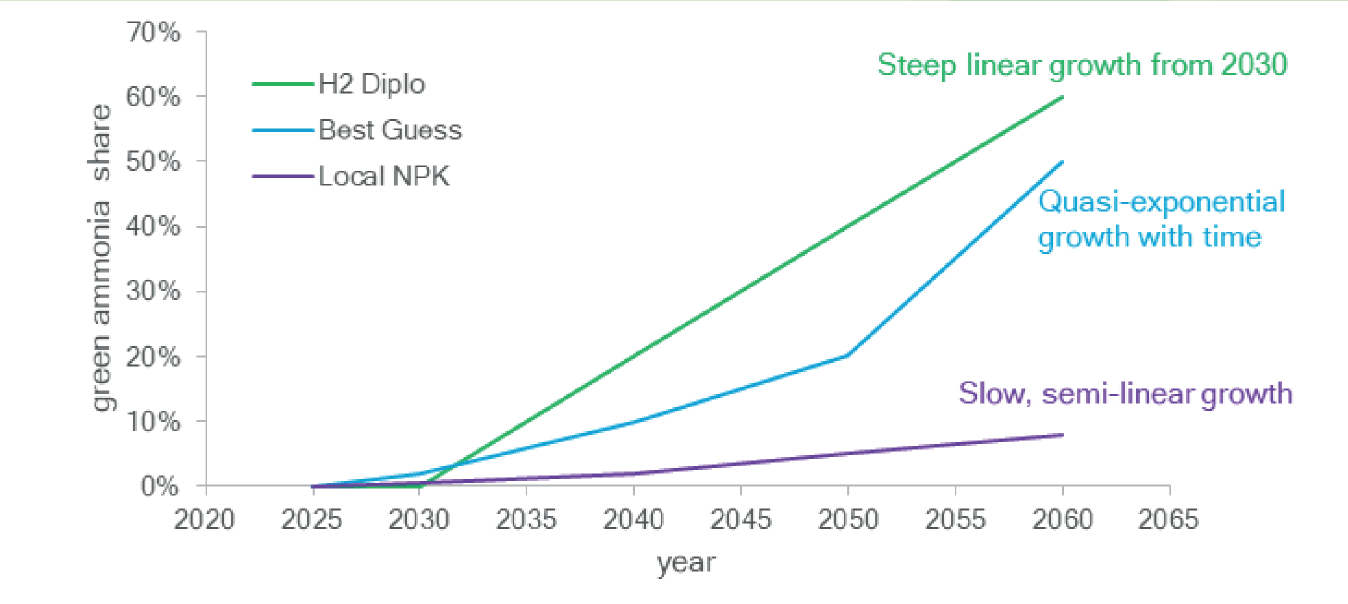

Figure 37: Green ammonia shares in Nigeria's total ammonia production under the two scenarios proposed in this study, with H2 Diplo's conservative scenario included for comparison.

Table 18 presents the projected total ammonia production under the proposed "best guess" scenario. The same assumptions and calculation methods were applied as in the analysis of the "H2 Diplo" scenario (results shown in Table 16). While the "best guess" scenario also allows for potential green ammonia exports, the comparatively lower projected shares over time result in reduced export volumes compared to those anticipated under the "H2 Diplo" scenario.

Year	NH3 production [Mt]			Local NH3 demand [Mt]	NH3 Exports [Mt]
	Grey	Green	Total		
2023	2,3	0,0	2,3	0,6	1,7
2030	2,8	0,1	2,9	0,7	2,1
2040	3,2	0,4	3,5	1,0	2,5
2050	3,2	0,8	4,0	1,3	2,7
2060	3,2	3,2	6,3	1,5	4,8

Table 18: Projected ammonia production for fertilisers based on 'best guess' scenario in million tons [Mt].

Assuming that ammonia continues to be exported in the form of urea and considering global urea market trends and future export projections, the 'best guess' scenario anticipates Nigeria's share in global urea exports to be approximately 8.4 % by 2030, increasing to 10 % by 2050, and reaching 17 % by 2060. Scenarios considering the production of large volumes for the global market may lead to lower prices, thereby enhancing the competitiveness and adoption of green fertilisers in the long run.

For the ‘local NPK’ scenario, which considers the production of NPK fertiliser precursor, specifically ammonium sulphate (GAS) and diammonium phosphate (DAP), using domestically produced green ammonia, the aim is to reduce reliance on imports and enhance Nigeria's fertiliser self-sufficiency. Table 19 presents the total demand for GAS and DAP in 2023, which is entirely covered by imports. Based on historical consumption patterns of these precursors, a trend analysis was conducted to forecast future demand values [122].

Year	GAS &DAP demand [t]	% Locally produced	Green NH3 feedstock [t]
2023	303,066	0%	0
2030	507,459	10%	13,089
2040	799,449	30%	61,860
2050	1,091,439	60%	168,908
2060	1,383,429	100%	356,825

Table 19: Projected demand for NPK precursors and required green ammonia feedstock

Under the ‘local NPK’ scenario, it is assumed that the required amount of these NH_3-based products will continue to rely on imports in the near term. However, a gradual substitution with locally produced precursors is projected, leading to complete domestic production by 2060. Table 19, illustrates the total demand for the precursors and possible fractions to be manufactured in the country, and shows an estimation of the corresponding quantities of green ammonia feedstock necessary for this local production.
According to these assumptions, relevant amounts of green hydrogen are only needed by 2040. A small-scale production site for demonstration purposes may be established until 2030. Thus, by 2030 a 0.5 % share of Nigerian ammonia production is green. This share ramps up to about 8 % by 2060 (Table 17).

As the fertiliser market is dominated by urea-based products[117] and expected green fertiliser costs might not be competitive or congruent with current pricing, the adoption rate of green ammonia-based NPK blends increases slowly over time, but stays relatively low.
Additional scenarios that consider the parallel development of large-scale green ammonia production aimed at export markets, alongside the integration of small-scale, decentralized concepts within the country (such as for the production of GAS and DAP), could also be explored in future works.

6.2.3. Potential Cost of Green Ammonia Produced in Nigeria
6.2.3.1. Methods
6.2.3.1.1. Scenario Development

Prior to estimating the costs associated with green hydrogen and ammonia production, various scenarios for producing green ammonia for fertilisers in Nigeria were analysed. This analysis aimed to explore different production pathways and assess their respective scales and feasibility within the country's context. The scenarios within this report are based on current data on global and Nigerian production and exports of urea, as it is the dominant product. The general trends in production and its potential capacity were extrapolated. Of these values, we calculated the amount of ammonia and its according H2-content to be produced.

Local NPK Scenario

For green hydrogen and ammonia, we estimated a general progression as shown in Table 20. This estimation is based on NPK blends used in Nigeria, for which the ammonia could be domestically produced instead of the current import of ammonia-based NPK precursors GAS and DAP. Production of green ammonia and subsequent transformation into DAP and GAS is assumed to take place in newly constructed facilities, while existing urea plants continue to operate using natural gas as their feedstock. Table 20 provides an overview of the projected total ammonia demand for fertilisers in Nigeria up to 2060, highlighting the share of green ammonia and the equivalent amount of green hydrogen required.

Year	Total NH_3 [t]	Green NH_3	Green NH_3 [t]	Green H2 [t]
2030	2,825,761	0,5 %	13,089	2,324
2040	3,228,581	2 %	61,860	10,984
2050	3,689,678	5 %	168,908	29,992
2060	4,231,645	8 %	356,825	63,358

Table 20: Overview over total ammonia and green ammonia production in the 'local NPK scenario' over time

Best Guess Scenario

The ‘best guess’ scenario is based on increasing urea exports out of Nigeria as a result of large-scale green ammonia production. This implies the establishment of newly built green ammonia facilities alongside the continued operation of existing natural gas-based plants. Table 21 provides an overview of the projected total ammonia demand for fertilisers in Nigeria up to 2060 under the considered scenario, along with the corresponding values for total green ammonia and hydrogen required.

Year	Total NH_3 [t]	Green NH_3	Green NH_3 [t]	Green H2 [t]
2030	2,812,672	0 %	0	0,0
2040	3,958,401	20 %	791,680	140,572
2050	5,277,869	40 %	2,111,147	374,859
2060	7,916,803	60 %	4,750,082	843,433

Table 21: Overview over total ammonia and green ammonia production in the 'best guess scenario' over time

A complete analysis and further details about the scenarios introduced above can be found in the section 'Scenarios for Green Ammonia Production in Nigeria.

6.2.3.1.2. Commodities

Natural gas
It is assumed that the current price of natural gas remains relatively stable, with only a slight increase over time. Starting in 2024 at €2.4 per million British thermal units (BTU), the price is projected to rise to €2.6 per million BTU by 2060 [123], [124], [125].

Water
Water costs are assumed to increase linearly from 300 Naira (approximately €0.16 per cubic metre, m^3), based on historical trends. Actual costs may vary depending on location.

Electricity for the grey process
For grey ammonia cost estimation, grid electricity prices are assumed at €0.13 per kilowatt-hour (kWh) at present, gradually decreasing to €0.06 per kWh by 2060. This reduction reflects the expected integration of lower-cost renewable energy sources into the national grid.

Renewable power generation
Costs for renewable power generation are assumed to decline over time (Figure 38) as technologies become more accessible. Electricity used for green hydrogen and green ammonia production is treated as a purchased commodity; thus, prices are higher than generation costs alone. Renewable power prices were calculated based on levelized costs of electricity [121], [126], [127], [128], [129] plus a fixed premium, decreasing by approximately 10–30% per decade. These prices are significantly lower than current electricity prices (see Uncertainties and Pitfalls), but it should not be assumed that consumers will automatically benefit from lower generation costs, as prices may remain stable despite reduced production costs.

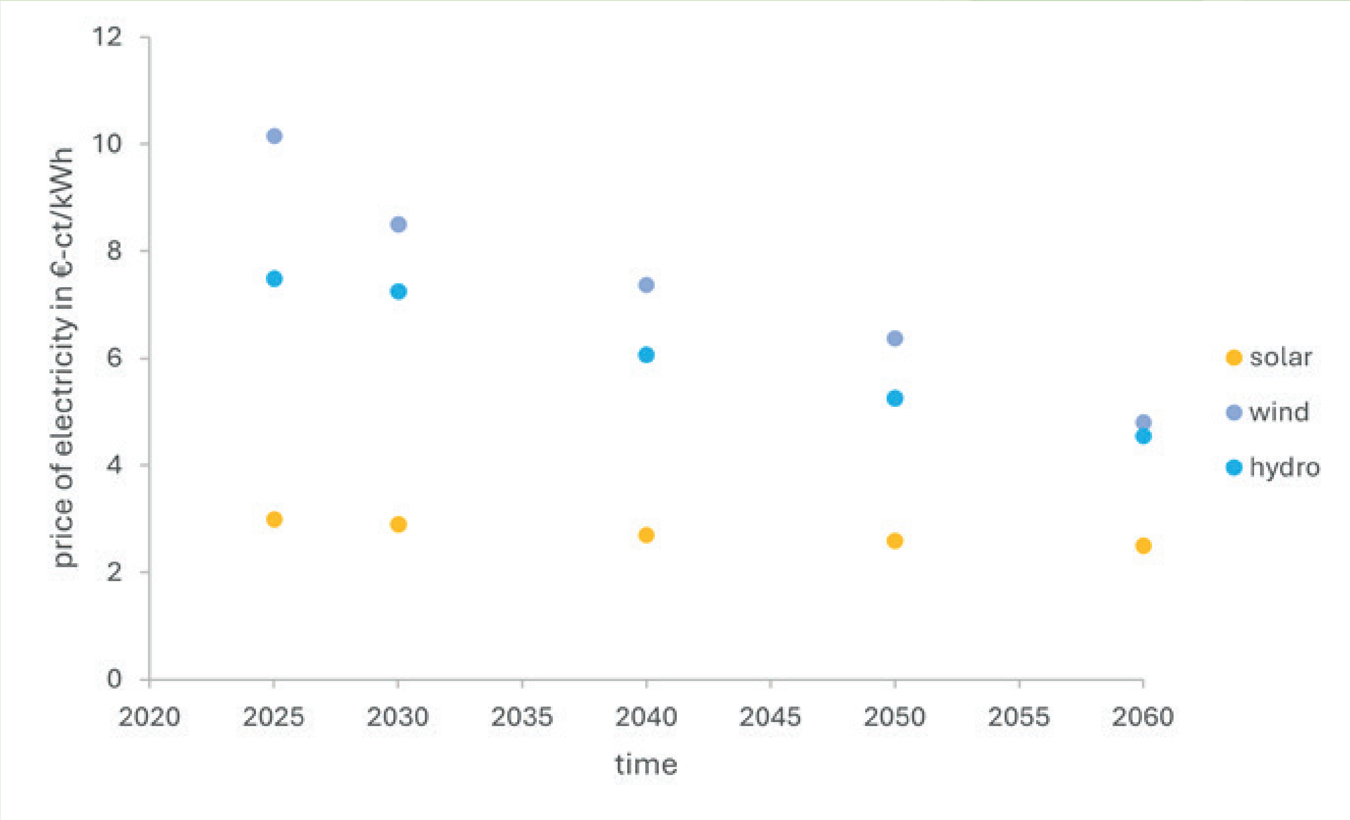

Figure 38: Price of electricity in €-Cent per Kilowatt-hour. Due to relatively low prices for solar, decrease over time is barely visible.

Annual Capital Expenditures

Total CAPEX can be calculated on an annual basis. This calculation considers that the intended period of use (runtime) might be longer than the period until refurbishment (lifetime). CAPEX includes direct (cost of stack) and indirect costs (e.g., balance of plant components), which are similarly expensive at about 1,500 €/kW. Refurbishment costs were estimated to be 5 % of direct CAPEX.

<u>Annual CAPEX before refurbishment</u>

$$\frac{\left(direct + indirect\ CAPEX\ \left[\frac{€}{MW}\right]\right) \cdot capacity\ [MW]}{lifetime\ [a]}$$

<u>Annual CAPEX after refurbishment</u>

$$\frac{refurbishment\ costs\ [\frac{€}{MW}] \cdot capacity\ [MW]}{runtime - lifetime\ [a]}$$

Annual total CAPEX

$$annual\ CAPEX\ before\ refurbishment\ \left[\frac{€}{a}\right] + annual\ CAPEX\ after\ refurbishment\ [\frac{€}{a}]$$

Annual Operational Expenditures
OPEX are linked to CAPEX and include, for example, costs for labor, water, and maintenance. OPEX was assumed to be 3% of CAPEX, although it could alternatively be calculated as the sum of all relevant costs if detailed data were available (labor, maintenance, electricity, services, taxes, water, etc.).

An overbuild factor accounts for renewable surplus in dedicated systems, resulting in additional full-load hours. This is particularly relevant in systems with increasing renewable capacity and available materials and technologies. For this study, overbuilding was assumed from 2030 onwards. Values for overbuilding are based on estimates from current European projects and literature, such as Knorr et al. [130], and vary between the two cost progression scenarios for hydrogen.

Annual OPEX

$$3\ \%\ total\ CAPEX[€]\ per\ a + \frac{capacity\ [MW] \cdot full\ load\ hours\ \left[\frac{h}{a}\right] \cdot overbuild\ factor}{cost\ of\ electricity\ [\frac{€}{MWh}]}$$

Parameter	**Renewable energy**		
	Solar	**Wind**	**Hydropower**
Annual full load hours	1800 h	1100 h	4600 h
Overbuild factor (optimistic)	2.4	3.2	1.5
Overbuild factor (slow)	1.5	2.5	1

Table 23: Overview over assumptions for power input.

Possible full load hours selected for this analysis were generally conservative (Table 23). Different locations might be better suited for one or the other technology. With a dedicated renewable energy production attached, hydrogen could be produced with levelized costs of electricity. However, CAPEX for renewables would need to be included. In this study, we assumed electricity to be a commodity and therefore, slightly more expensive.

Annual Total Costs

$$annual\ total\ CAPEX\ \left[\frac{€}{a}\right] + annual\ OPEX\ \left[\frac{€}{a}\right]$$

Annual H_2- production volume

<u>Annual production in MWh</u>

$$capacity\ [MW] \cdot full\ load\ hours\ \left[\frac{h}{a}\right] \cdot overbuild\ factor \cdot electrolyser\ efficiency\ [\%]$$

Electrolyser efficiency for proton exchange membrane (PEM) was assumed to be 5 % lower than alkaline water electrolysis (AWE), due to its slightly lower technological maturity. It is not unreasonable to assume that efficiency may increase over time, which is one of the reasons for decreasing costs over time (cf. cost progression).

Conversion from Megawatt-hours (MWh) into Kilogram or from Kilogram to MWh can be calculated with the energy density of hydrogen. This conversion is necessary for the calculation of the size of the plant and its necessary capital investment.

LCOH: Levelized Costs of H2

Total costs can be broken down in € per kilogram by dividing through annual production volume based on capacity and full load hours.

Costs of Hydrogen in € per kilogram

Costs of Hydrogen in € per kilogram

$$\frac{annual\ total\ CAPEX\ \left[\frac{€}{a}\right] + annual\ OPEX\ \left[\frac{€}{a}\right]}{annual\ production\ \left[\frac{kg}{a}\right]}$$

Cost progression

We assume that hydrogen costs for solar PV and wind decline over time after 2040 by 15% for AWE and 25% for PEM, reflecting their levels of technological maturity and upscaling potential. Hydropower is an exception, as it is not scalable in the same way as solar PV or wind turbines. For hydropower, costs are projected to decline by 7.5% (AWE) and 12.5% (PEM) between 2040 and 2050, and by 3.75% (AWE) and 6.25% (PEM) until 2060. The difference between these two cost progressions primarily reflects variations in surplus renewable capacity (overbuilding) from 2030 onwards.

Necessary Investment

Investment calculations are based on CAPEX and the annuity of green hydrogen plants, adjusted for the slow cost progression to approximate overall sunk costs. Capacities built in previous years were subtracted from the calculation.

6.2.3.1.4. Ammonia

The Levelized Cost of Ammonia (LCOA) represents the average cost per unit of producing ammonia over the lifetime of the plant. It can be expressed by the following general equation:

$$LCOA = \frac{Annualized\ CAPEX\ [€] + Annual\ OPEX\ [€]}{Annual\ ammonia\ production\ \left[\frac{tons}{year}\right]}$$

An explanation of how CAPEX and OPEX costs are derived is provided below.

Annual Capital Expenditures

CAPEX for green ammonia production consists of the investment costs for the air separation unit (ASU) and the Haber-Bosch plant.

Overall CAPEX= 〖CAPEX〗_(Haber-Bosch)+ 〖CAPEX〗_ASU

Overall CAPEX needs to be transformed into the annual payments required to repay the investment costs. The annuity was calculated using the following equation, assuming a payback period n of 20 years and an interest rate i of 12 %.

$$Annualized\ CAPEX\ = overall\ CAPEX\ \cdot \left[\frac{i}{1-(1+i)^{-n}}\right]$$

The payback period was selected based on representative depreciation times for this type of technology. An interest rate of 12% was chosen as an average value, reflecting the economic context in Nigeria and similar projects in the field.

For comparison, the costs of grey ammonia production were also calculated. In this case, the overall CAPEX was considered as the investment for the SMR and Haber-Bosch units.

Annual Operational Expenditures (OPEX)
Annual OPEX include fixed operational costs, feedstock, and electricity. Fixed OPEX covers operational expenses such as maintenance, salaries, and insurance. For this analysis, it was assumed to be 3% of total CAPEX per year, in line with literature values ranging from approximately 2–5% [131], [132], [133].

For green ammonia, feedstock costs correspond to the cost of green hydrogen delivered to the process. For grey ammonia, feedstock costs consist of natural gas and water for the SMR unit. Electricity costs for both processes cover the energy required to operate main units, heat exchangers, and other auxiliary equipment. Electricity and water costs associated with green hydrogen production are not included here, as they are already accounted for in the feedstock cost of green hydrogen.

An overview of additional parameters and values used for ammonia production cost calculations is presented in Table 24

Process parameter	Unit	Ammonia production	
		Gray	Green
Electricity	GJ/tNH_3	2.4	2.4
Natural gas	GJ/tNH_3	27.3	-
Water	t/tNH_3	1.3	-
Green Hydrogen	t/tNH_3	-	1.178
CAPEX Haber-Bosch	€$/tNH_3$	500	500
CAPEX SMR	€$/tNH_3$	700	-
CAPEX ASU	€$/tNH_3$	-	95

Table 24: Additional parameters for ammonia cost estimations.

6.2.3.1.5. Uncertainties and Pitfalls

Limited Scope and Data Availability
Not all necessary data for the calculations were readily available, so assumptions had to be made based on literature data that were not specific to Nigeria.
For this brief analysis of ammonia costs, we assumed that power and hydrogen for ammonia production were commodities to be purchased. Therefore, potential CAPEX for renewable electricity generation was not included.

These costs would be borne by the provider of the commodity, e.g., a solar photovoltaics (PV) plant. Nigeria currently has no system to trade the “green” attribute of renewable power from the grid. Therefore, to produce green hydrogen or green ammonia, a complete value chain must be established for each specific project. This can hinder small-scale investments, as the financial burden per project must cover the entire value chain—from renewable generation to green ammonia or green fertilizers.

Additionally, any infrastructure that may be required to transport electricity or hydrogen to the ammonia plant, or to export products, was not considered. Investments in large-scale infrastructure are typically addressed at the state or federal level and often involve public-private partnerships.

Furthermore, costs related to downstream products, such as urea, diammonium phosphate (DAP), and ammonium sulfate (AS), were not considered. These would include additional infrastructure, processing facilities, and logistical requirements, which were beyond the scope of this study.

Power for Hydrogen and Ammonia

Due to fewer full-load hours, onshore wind could be more costly than other options. Often, a combination of onshore wind and solar PV can create favorable conditions for industrial applications, as nightly winds and daily solar irradiation can complement each other. Future work could explore such combinations, as well as local (micro-)grids that might operate entirely on renewable energy. Additionally, some locations are better suited for wind turbines, while others receive more solar irradiation. In theory, northern Nigeria may be suitable for both wind turbines and solar PV plants; however, ongoing conflicts [134], [135] may make such projects too risky and, consequently, too expensive.

Hydropower is generally a reliable source of renewable energy with many full-load hours. However, its potential is often naturally limited, and constructing new hydropower dams can be a slow process. As existing dams are already in operation, dedicating their electricity exclusively to one application may not be feasible. Even if the electrolyser capacity is smaller than the dam’s output, much of the dam’s electricity might still be required by the local Nigerian grid, leaving little to spare. In a ‘best guess’ scenario, the renewable electricity needed for green hydrogen production will exceed the currently installed capacity of Nigeria’s hydropower dams, which is about 2.7 GW [136], by 2040. Some hydropower projects are planned between 2030 and 2035, which could increase capacity to approximately 8.4 GW [75]. However, in practice, not all turbines may be installed, and theoretical capacities may not be fully achieved [75].

Costs of Ammonia Production

Costs for ammonia may vary by location, depending on prices paid by companies for commodities or labor. Since not all commodity prices are determined by the market, some may be higher, and prices may respond slowly—or not at all—to new developments [137].

In addition, the assumptions reflect levelized costs of electricity generation plus a mark-up for additional costs, such as grid fees, taxes, or annuity costs for power lines from the renewable site. It was also assumed that electricity costs would decrease over time as renewable capacity in the system increases. These values are lower than the current electricity prices for companies, which are approximately 210 Naira per kilowatt-hour [137], [138] (about 0.11 €/kWh). Without dedicated renewable power generation, companies would likely pay at least 210 Naira plus a potential green premium.

Moreover, the cost calculation is standardized to € per ton of ammonia, based on an average of plant sizes ranging from 300,000 to 1 million tons per year of ammonia production. Therefore, differences in cost due to scaling effects are not captured, particularly for significantly smaller decentralized units or for very large-scale facilities beyond this range. Ammonia plants are generally scalable and built in various sizes worldwide, but they are typically large. Small-scale demonstration plants may incur higher CAPEX because some components are not standardized.

Future CO_2 pricing mechanisms could also influence the viability of producing blue or green ammonia. For this scenario analysis, it was assumed that potential future CO_2 prices would not prohibitively affect blue ammonia production.

6.2.3.2. Results

The following section highlights hydrogen for ammonia, the potential costs of ammonia, and the necessary investments for the scenarios

6.2.3.2.1. Hydrogen Demand

The green hydrogen demand for green ammonia varies strongly within the different scenarios, as shown in the table below (Table 25). Depending on the velocity of the underlying green ammonia ramp up, hydrogen demand can range from 0 to about 10,000 tons by 2030 and climb up to 63,000 to 843,000 tons by 2060.

Year	Local NPK [t]	Best Guess [t]	H2 Diplo [t
2030	2,324	10,192	0
2040	10,984	62,477	140,572
2050	29,992	140,572	374,859
2060	63,359	562,288	843,437

Table 25: Overview over hydrogen demand for green ammonia in the different scenarios.

Overall, up to 1.2 gigawatt (GW) installed capacity of electrolysers is needed to produce green hydrogen in the ‘local NPK scenario’, up to 11 GW in the ‘best guess scenario’ and up to 16 GW in the ‘H2 Diplo’ scenario with our assumptions and calculations for green ammonia production alone, as highlighted in Figure 39. Differences between AWE and PEM are often below 0.1 GW. Across both technologies, hydropower requires the least installed capacity, as it yields the highest full load hours. However, the overall potential may be limited by available sites for hydropower dams (cf. Uncertainties and Pitfalls).

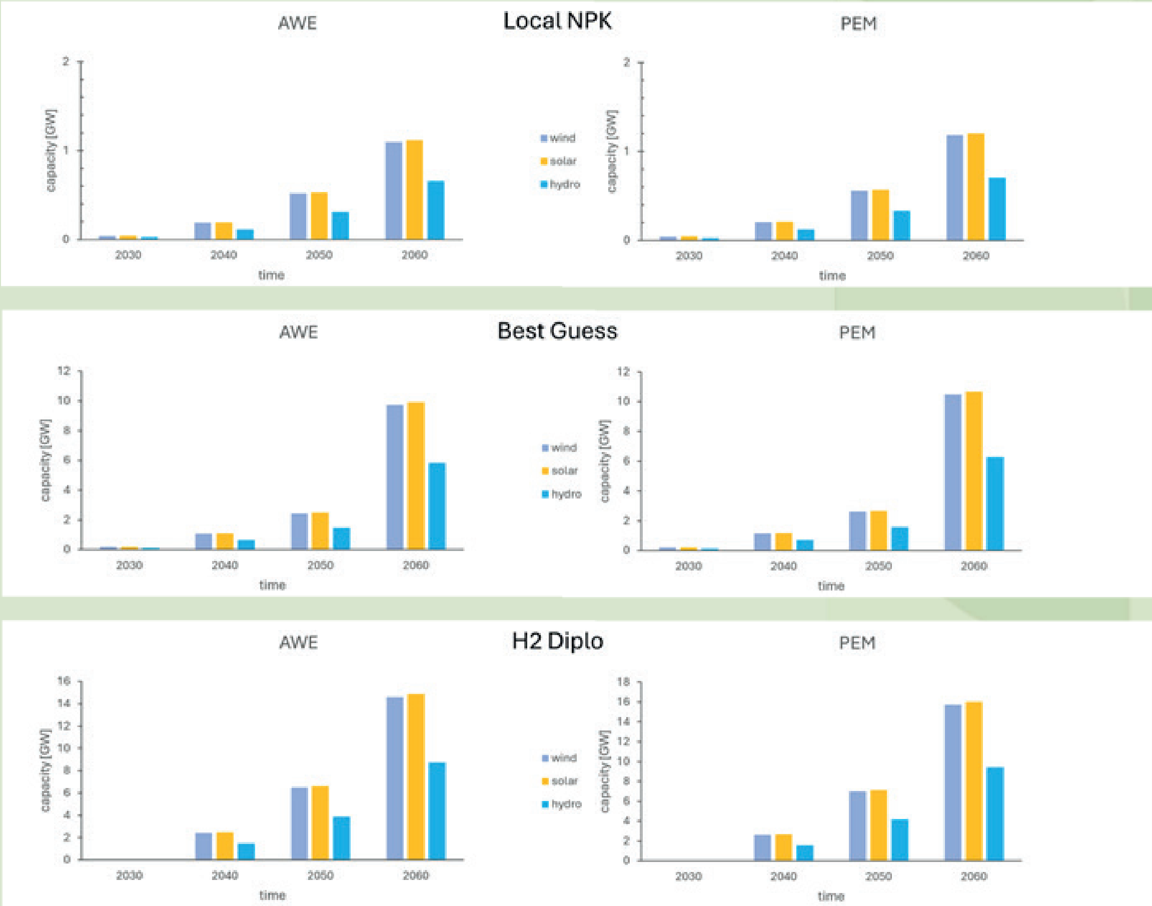

Figure 39: Required electrolyser capacity in gigawatts for AWE (left) and PEM (right) under the scenarios 'Local NPK', 'Best Guess', and 'H2 Diplo', across three renewable energy sources: onshore wind, solar PV, and hydropower.

Costs for hydrogen are expected to decrease over time as the costs of electrolysers and dedicated renewable energy production decline. Differences between alkaline water electrolysis (AWE) and proton exchange membrane electrolysis (PEM) also diminish over time as the technologies mature.

In the first few years, costs may remain high during the ramp-up phase. However, with increasing production and integration of renewable electricity, costs are projected to decrease significantly under the optimistic cost progression and more moderately under the slower scenario.

Due to fewer full-load hours, onshore wind appears to be the least cost-effective renewable energy source compared to hydropower and solar photovoltaics (PV), as shown in Figure 40. Depending on the location, wind speeds at different heights, and solar irradiation, this generalization may not hold true for all of Nigeria.

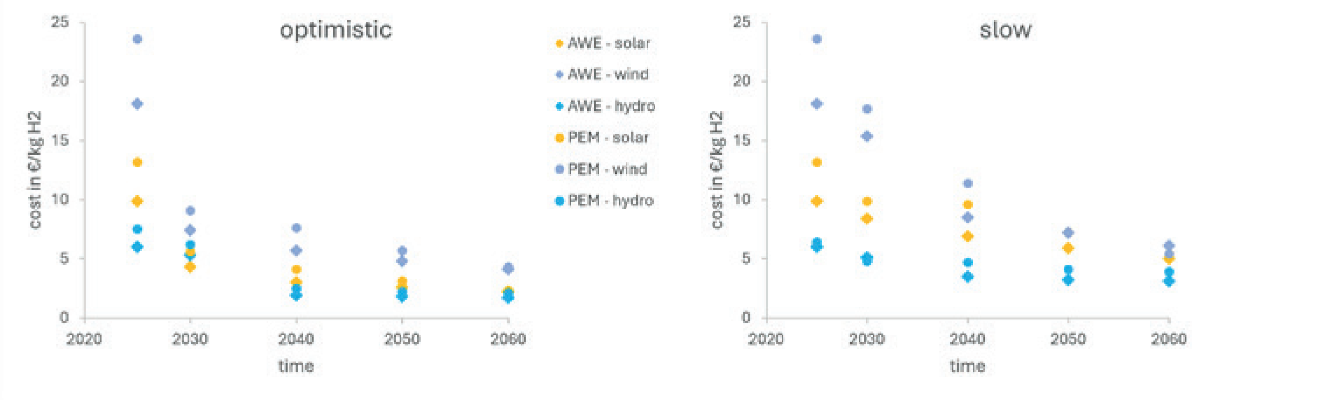

Figure 40: Hydrogen costs over time for AWE and PEM across three renewable energy sources (onshore wind, solar PV, hydropower). Left: optimistic cost progression; right: slow cost progression.

6.2.3.2.2. Necessary Investment in Green Hydrogen Production

Investments in green hydrogen scale directly with the installed capacity of the electrolyser. Consequently, fewer full-load hours—as is the case with onshore wind in Nigeria—have a significant impact on levelized costs and future prices of green hydrogen.

The total investment required for the 'Local NPK' scenario using AWE technology could reach approximately €1.1 billion by 2060. In the 'Best Guess' scenario, higher green ammonia production requires greater green hydrogen capacity, resulting in total AWE investments of around €9 billion. The results shown in Figure 41 reflect the slow cost progression, as it represents a more conservative assumption and may account for additional challenges, such as high inflation or costs for specific components.

Figure 41: Necessary investments over the coming decades for the ‘Local NPK’, ‘Best Guess’, and ‘H2 Diplo’ scenarios.

Over time, the PEM technology matures, and CAPEX decreases, for example due to less iridium-intensive catalysts. In the 'best guess' scenario, necessary investments for PEM can amount to about 8.8 billion Euro by 2060. In the 'local NPK' scenario with its lower hydrogen demand, investment may lie at about 1.1 billion Euro until 2060.
In comparison to the 'local NPK' and the 'best guess' Scenario, investments for the 'H2 Diplo' scenario can reach 13.5 billion Euro by 2060 with an average of about 12 billion Euro.

6.2.3.2.3. Potential Costs of Green Ammonia

To analyze the potential costs of green ammonia production in Nigeria, the costs associated with current grey ammonia production in the country are first presented as a basis for comparison.

Figure 42 provides a breakdown of the potential costs related to grey ammonia production under current industry conditions in Nigeria's urea sector. All values presented here were calculated based on information and assumptions derived from publicly available sources rather than direct data from producers. Therefore, they should be considered as reference points or guidelines, not precise or actual figures.

As shown, current production costs are primarily driven by annualized capital investment. However, if production reaches full capacity in the coming years, the annualized CAPEX per unit of output is expected to decrease due to improved utilization of the installed infrastructure. Since current installations are expected to be fully depreciated after 2040, CAPEX-related costs will decline, being limited primarily to renovation and replacements. In contrast, production costs for grey ammonia will remain highly sensitive to fluctuations in natural gas prices.

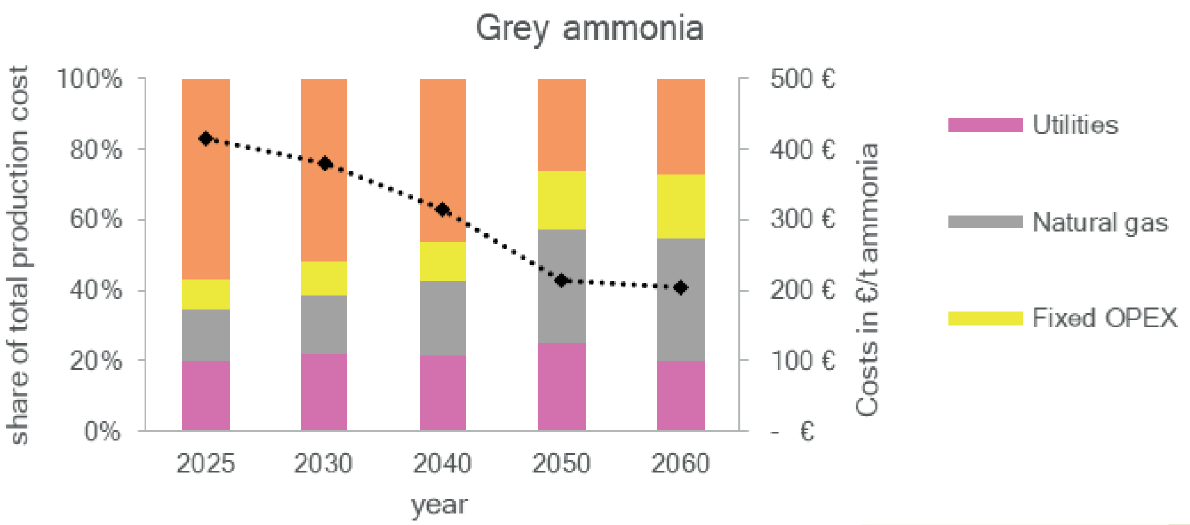

Figure 42: Production costs breakdown for grey ammonia in Nigeria.

Regarding green ammonia, the analysis indicates that the most economically viable conditions for green hydrogen production in Nigeria involve using hydropower-generated electricity in combination with Alkaline Water Electrolysis (AWE) technology. For this reason, these parameters have been selected as the basis for the cost breakdown model related to green ammonia production, as presented in Figure 43.

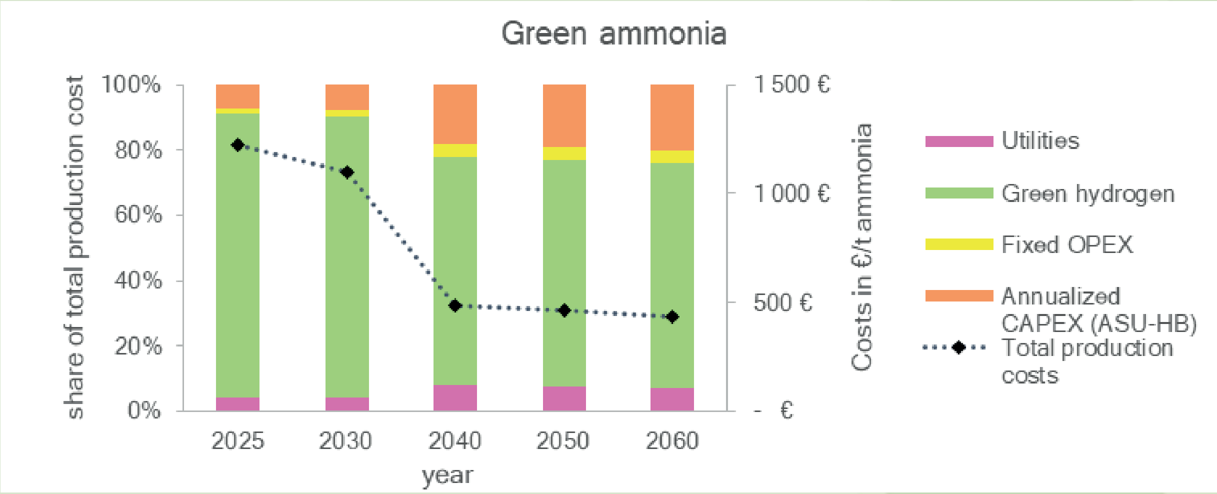

Figure 43: Production costs breakdown for green ammonia via hydropower and AWE with the optimistic cost progression of green hydrogen.

The cost of green ammonia production is largely driven by the cost of hydrogen produced via electrolysis, which in turn is influenced by renewable electricity prices and the type of technology used. In the early years, the high cost of green hydrogen makes green ammonia production relatively expensive, with hydrogen accounting for approximately 70–90% of total production costs.

Current and near-term production prices remain high due to the early stage of the technology. However, as the technology and value chain mature, renewable electricity infrastructure improves, and mass deployment occurs, the levelized cost of hydrogen (LCOH) is expected to decrease after 2040. Under an optimistic yet feasible scenario, where LCOH declines by at least 60% by 2040, green ammonia production costs could fall below €500 per ton.

In comparison, grey ammonia prices are likely to remain lower, although they could still be significantly affected by future natural gas prices (assumed to remain nearly constant in this analysis) and the potential introduction of carbon pricing in Nigeria or at its borders [139]. This could lead to a breakeven point after 2040, where prices for green and grey ammonia converge.

6.2.3.2.4. Impact of Different Renewable Energy Sources on the Potential Cost of Ammonia

Due to the initially high cost of green hydrogen, green ammonia prices are strongly influenced by the choice of renewable energy sources. Over time, as the cost of green hydrogen decreases, green ammonia production becomes more affordable as well (Figure 44).

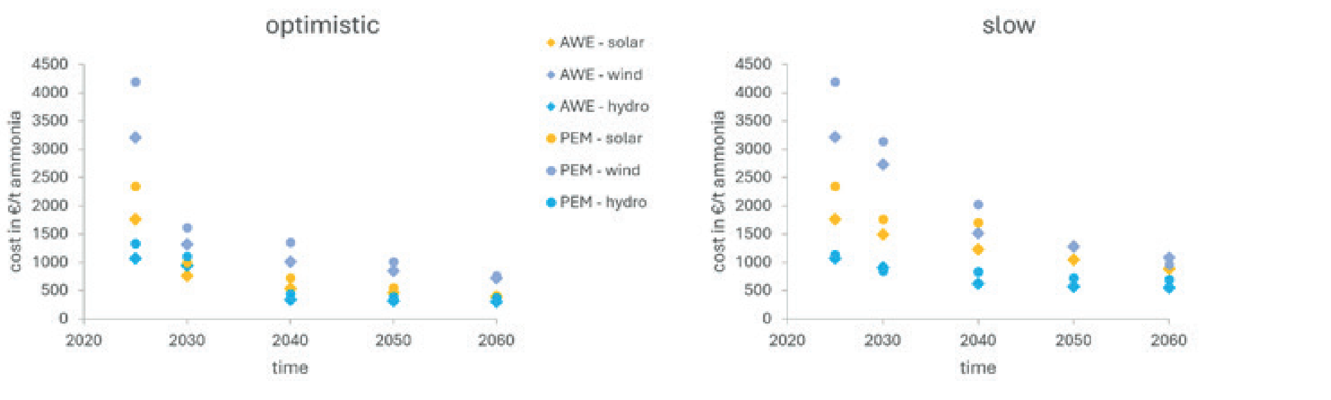

Figure 44: Hydrogen costs in € per ton of ammonia for two cost progression scenarios. Left: optimistic cost progression; right: slow cost progression.

With hydrogen costs ranging from approximately €2 to €20 per kilogram (kg), green ammonia production costs vary between about €450 and €4,000 per ton, depending on the time frame and cost progression. Due to the strong influence of hydrogen costs on ammonia prices, green ammonia costs largely follow the cost progression of hydrogen. These costs differ significantly from the current costs of grey ammonia in Nigeria, particularly during the ramp-up phase.

Fertilizer prices in Nigeria are around €380 per metric ton for urea and €450 per metric ton for NPK blends [115]. However, prices for farmers can be approximately 42% higher when accounting for packaging, transport, and distribution [140]. Global ammonia prices rose to about USD 1,000 per short ton following the war in Ukraine [141].

Given these high production costs and the resulting prices for consumers, selling green fertilizers within Nigeria may be challenging during the first decades. Export could still be an attractive option, even at high production costs.

6.2.3.2.5. Necessary Investments in Green Ammonia

To produce green ammonia, dedicated facilities must be constructed and financed. With CAPEX of approximately €600 per ton of ammonia and relatively high expected returns on investment due to the perceived risks of lending, initial investments can vary significantly, especially during the first five years. For the investment costs shown in Table 26, annuities for borrowed funds covering fixed operational expenditures and commodities are not included. Additionally, these values reflect only green ammonia production and do not account for any additional capital expenditures.

Year	Local NPK	Best Guess	H2 Diplo
2030	8.8 million €	39 million €	0 €
2040	33 million €	199 million €	534 million €
2050	81 million €	336 million €	0.9 billion €
2060	160 million €	1.8 billion €	2.3 billion €
Total	283,000,000 €	2,400,000,000 €	3,700,000,000 €

Table 26: Investment costs for the production of ammonia in the 'local NPK' and the 'best guess' scenario, as well as the 'H2 Diplo' scenario. Values are rounded to reduce risk of feigning false

Overall, up to 2.4 billion Euros investment into green ammonia plants are needed in the 'best guess' scenario and up to 283 million Euros in the 'local NPK' scenario, not including any necessary additional infrastructure for transport and export of green ammonia, such as shipping terminals.

6.2.3.2.6. Overview of Necessary Investments

An overview over potential investment is shown in Table 27 below. Approximate investment for renewables is based on averages for renewables in Africa sourced from IRENA [127]. As the renewable generation of solar and wind power is overbuilt in this analysis in comparison to the electrolyser for more full load hours, large investments might be necessary.

T*able 27: Overview over potential needed investments for green ammonia based on the 'local NPK' and 'best guess' and 'H2 Diplo' scenarios. Values are rounded to reduce risk of false accuracy.*

	Local NPK	Best Guess	H2 Diplo
Approx. Renewables	*~3.4 billion €*	*~30 billion €*	*~46 billion €*
Green Hydrogen (average)	*~1 billion €*	*~8.2 billion €*	*~12 billion €*
Green Ammonia	*~0.3 billion €*	*~2.4 billion €*	*~3.7 billion €*
Total	**~7.4 billion €**	**~41 billion €**	**~61 billion €**

Overall, substantial investments across all three scenarios are required to establish a complete value chain. If green fertilizers are to be produced, additional investment in chemical plants must be considered. Furthermore, public-sector investments may be necessary, for example, in roads or the national grid. Large-scale exports could also require additional transport and shipping infrastructure.

IHowever, this opportunity comes with unique challenges. Firstly, the required investments for the different scenarios can amount to billions of euros, which would also necessitate additional investments in energy and transport infrastructure and a rapid ramp-up of renewable capacity.

Secondly, Nigeria already produces grey ammonia-based urea for fertilization in relatively new facilities. Retrofitting these plants to use green hydrogen may be economically unfeasible, making a transition to blue ammonia a more viable pathway. Since urea synthesis only utilizes a portion of the CO_2 generated during ammonia production, the remaining emissions could be captured and permanently stored to move the overall process toward carbon neutrality. When competing with blue ammonia produced in existing, fully depreciated plants, the commodity prices of green hydrogen and green ammonia must decrease rapidly over the coming decades; otherwise, adoption rates of green products may remain low. Depending on future regulatory frameworks and global urea markets, converting grey or blue urea plants to green urea facilities using climate-neutral carbon sources could become economically attractive in the future.

Moreover, the domestic market for green ammonia-based fertilizers may be limited by prices and consumer purchasing power. The potential costs presented in this study could be influenced by factors such as lower electricity tariffs for green hydrogen production or subsidy mechanisms. Since prices encompass more than production costs and accumulate along the value chain, it is uncertain how much consumers would actually benefit.

Ultimately, large-scale production of green ammonia-based fertilizers for the domestic market seems unlikely under current conditions. However, there is significant potential for exports if the current climate neutrality goals of various nations withstand despite changing global political dynamics.more than just the production costs and accrue along the value chain, it is uncertain though how much consumers would benefit in actuality.

7. RECOMMENDATIONS AND FUTURE PERSPECTIVES

7. RECOMMENDATIONS AND FUTURE PERSPECTIVES

Based on the findings of this study, the following recommendations are proposed for green ammonia production in Nigeria. These cover policy, strategy and regulatory frameworks, capacity building and research and development, investment, as well as technology and infrastructure.

7.1. Policy, strategy and regulatory framework

- **Establish a National Green Hydrogen and Ammonia Roadmap**

  Nigeria should develop and adopt a comprehensive national strategy for green hydrogen and green ammonia, integrating these sectors into the country's broader energy transition and industrialisation agenda. This roadmap should articulate clear targets for renewable energy integration, green hydrogen and ammonia production, and fertiliser self-sufficiency, with defined milestones for 2030, 2040, 2050 and 2060.

- **Harmonize and Strengthen Policy Instruments**
  Existing policies, such as the Renewable Energy Master Plan (REMP), National Renewable Energy and Energy Efficiency Policy (NREEEP), National Water Resources Bill, the National Water Policy, the National Agricultural Technology and Innovation Policy and related acts, should be updated to include explicit support for green hydrogen and ammonia. This includes establishing a dedicated regulatory framework that covers safety, environmental standards, certification, and market access for green products. In addition, regional frameworks such as the ECOWAS Green Hydrogen Policy and Strategy Framework and the ECOWAS Green Hydrogen Regional Strategy and Action Plans should be integrated into Nigeria's national policy architecture to ensure alignment with West African regional objectives and leverage cross-border opportunities.

- **Create Enabling Incentives and Market Signals**
  Introduce targeted fiscal and non-fiscal incentives (e.g., import duty waivers, feed-in tariffs, green certificates, and guaranteed offtake agreements) to lower the investment risk for early movers. Policies should also encourage domestic use of green ammonia for fertiliser and explore export opportunities.

- **Foster Inter-Ministerial and Stakeholder Coordination**
  Establish a high-level Green Hydrogen and Ammonia Task Force comprising representatives from the Ministries of Power, Environment, Agriculture, Industry, Finance, and Science & Technology, as well as private sector, research institutions NGOs, and civil society. This body should coordinate policy, investment, and capacity-building actions, and serve as a one-stop shop for project developers.

7.2. Capacity building/Research and development

- **Develop Human Capital and Technical Expertise**
  Invest in specialized training programs at universities, polytechnics, and vocational centres focused on hydrogen technologies, electrolysis, ammonia synthesis, plant operations, and safety standards. Encourage scholarships, internships, and partnerships with international centres of excellence.

- **Promote Applied Research and Innovation**
  Establish dedicated research funding for green hydrogen and ammonia, supporting both fundamental and applied research. Prioritize pilot and demonstration projects that can validate technologies under Nigerian conditions, including water resource management for electrolysis and integration with renewable energy sources.

- **Facilitate Knowledge Exchange and International Collaboration**
  Organize regular forums, workshops, and exchange programs with leading international hydrogen and ammonia research hubs. Encourage Nigerian participation in global hydrogen alliances and standard-setting bodies.

- **Build Local Supply Chains and Technical Services**
  Support the development of indigenous engineering, procurement, and construction (EPC) capabilities for green hydrogen and ammonia projects, reducing reliance on imported expertise and equipment over time.

7.3. Investment

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- **Mobilize Public and Private Capital**

Leverage public funds to de-risk private investments through guarantees, blended finance, and viability gap funding. Proactively engage international development banks, climate finance facilities, and green bonds to support large-scale infrastructure and pilot projects.

- **Develop Innovative Business Models**

Encourage public-private partnerships (PPPs), consortia, and joint ventures between government, private sector, and international investors. Consider models such as build-own-operate-transfer (BOOT) for infrastructure, and anchor demand agreements with fertiliser producers.

- **Ensure Investment Transparency and Bankability**

Establish transparent project pipelines, standardized contracts, and clear regulatory processes to enhance investor confidence. Develop robust project feasibility studies, including technical, environmental, and social impact assessments.

- **Adopt a Phased Investment Approach**

Begin with small-scale demonstration and pilot projects in regions with high renewable energy potential (e.g., North-East solar, Middle Belt hydro), scaling up to commercial plants as market, regulatory, and technical readiness improves.

7.4. Technology and infrastructures

- **Accelerate Renewable Energy Deployment**
  Prioritize investment in solar, wind, and hydropower projects to supply cost-competitive electricity for green hydrogen production. Facilitate grid integration and off-grid solutions for remote fertiliser plants.

- **Develop Hydrogen and Ammonia Production Facilities**
  Support the establishment of state-of-the-art electrolysis and ammonia synthesis plants, with modular designs that can be scaled as demand grows. Ensure facilities meet international safety and environmental standards.

- **Upgrade Water Infrastructure**
  Given the water intensity of electrolysis, invest in ultrapure water production systems, sustainable water sourcing (including desalination and wastewater recycling where appropriate), and robust water management frameworks to avoid competition with local communities and agriculture.

- **Expand Storage, Transport, and Export Infrastructure**
  Plan and invest in hydrogen/ammonia storage, pipelines, and export terminals, leveraging Nigeria's strategic location for potential exports to Europe and other markets. Integrate with existing gas and fertiliser infrastructure where feasible.

7.5. Next steps

Nigeria's energy landscape, infrastructure base, and industrial capacity demonstrate strong potential for the country to play a pioneering role in green hydrogen and green ammonia production in West Africa. Taking the initial steps to leverage this potential alongside the implementation of the recommendations outlined above will help build practical knowledge of green hydrogen technologies and applications. It will also pave the way for the development of Nigeria's first green ammonia pilot plant.

- **Enhanced practical knowledge of green hydrogen technologies**: This objective can be achieved by developing initiatives that support scientific and technical studies on green hydrogen, with a focus on applications that align with Nigeria's socioeconomic context. Such efforts will enable key stakeholders to explore the feasibility of integrating green hydrogen into various sectors, including transportation, gas, petroleum, steel, and electricity, thereby identifying practical entry points for mainstream adoption.

- **Partnership for the first green ammonia pilot:** The proposed pilot will serve as a full-scale, pioneering facility, acting as a demonstration platform and knowledge hub to support the expansion of green fertiliser production in Nigeria and across West Africa. Its successful implementation will require a strong, multi-stakeholder partnership involving an existing fertiliser plant, with the Nigerian government providing a dedicated investment framework that offers incentives, ensures legal and regulatory stability, and guarantees investor protection. International technical and financial partners will also play a key role in supporting the pilot through expertise, technology, and funding.

GENERAL CONCLUSION

The Nigeria4H2 project was developed in response to the growing need for Nigeria to address its energy deficits and fertilizer supply challenges while transitioning to a more sustainable and resilient economy. Despite abundant fossil and renewable energy resources, Nigeria continues to face persistent electricity access limitations, particularly in rural areas, and relies heavily on fertilizer imports, which undermines national agricultural productivity. The project aimed to explore the feasibility of establishing a green hydrogen economy in Nigeria, with a focus on developing a green ammonia value chain to support domestic fertilizer production and contribute to the country's energy transition.

Developed and coordinated by WASCAL with financial support from the German Federal Ministry of Research, Technology and Space (BMFTR) , the project conducted a comprehensive assessment of Nigeria's technical, economic, infrastructural, and policy environment. The overall goal was to investigate the potential for green hydrogen and the enabling framework for producing fertilizers based on green ammonia in Nigeria. Special attention was given to renewable energy availability, hydrogen production costs, water resource adequacy, and the infrastructure required to support a new green ammonia industry.

The study confirms that Nigeria possesses considerable renewable energy potential. Hydropower capacity is estimated at over 14,000 megawatts, while solar irradiance levels range from 3.5 to 7.0 kWh/m²/day, covering large swathes of the northern and central regions. Biomass and wind resources, although more site-specific, offer additional potential. Water availability from surface and underground sources is also sufficient to support electrolysis-based hydrogen production, especially if managed through integrated resource planning. Nigeria is theoretically capable of producing more than 16,000 terawatt-hours of green hydrogen annually, reinforcing its prospects as a future green energy hub.

The realisation of this potential, however, depends on a strong alignment across sectors and actors. The cross-sectoral assessment conducted in this study reveals that although Nigeria has various existing policies in the energy, gas, fertiliser, water, and environmental domains, these frameworks remain fragmented and not yet tailored for green hydrogen or ammonia development. Addressing this policy incoherence and fostering synergy between sectors, especially energy planning, agricultural policy, water resource governance, and climate strategies, is vital for a coordinated rollout. In terms of stakeholder engagement, the study identifies a wide array of actors that must be involved, including federal ministries (Power, Environment, Agriculture, and Water Resources, Economic), regulatory agencies (NERC, NESREA), public institutions such as the Rural Electrification Agency and the National Council on Climate Change, as well as the private sector (energy developers, fertiliser producers, logistics providers, etc.), research institutions, and international development partners. Their collective participation will be key to driving investment, ensuring policy coherence, and building local capacity to support this emerging industry.

Green ammonia was chosen as a key application for green hydrogen due to its strategic importance in Nigeria's fertiliser market. Three development scenarios were explored in the study. The "Local NPK" scenario focuses on producing green ammonia to supply domestic NPK fertiliser plants, with an estimated annual production of around 356,825 tons by 2060. The "Best Guess" scenario envisions a mix of domestic consumption and moderate export, leading to a projected annual output of 3.17 million tons by 2060. The most ambitious, the "H2 Diplo" scenario, anticipates Nigeria emerging as a regional exporter of green ammonia, with production reaching 4.75 million tons per year by 2060. Across these scenarios, the levelized cost of hydrogen is projected to range between 2.8 and 3.5 euros per kilogram in the near term, with the potential to fall to about 1.5 euros by 2050 under favourable market and technology conditions.

The investment needs across the three scenarios are significant. For the "Local NPK" scenario, the total investment required is approximately 7.4 billion euros, comprising around 3.4 billion euros in renewable energy, 1 billion euros in hydrogen production, and 0.3 billion euros in ammonia plants. In the "Best Guess" scenario, the required investment rises to roughly 41 billion euros—30 billion euros for renewable energy, 8.2 billion euros for hydrogen, and 2.4 billion euros for ammonia production. The most ambitious scenario, "H2 Diplo," calls for approximately 61 billion euros in total investments, broken down into 46 billion euros for renewables, 12 billion euros for hydrogen, and 3.7 billion euros for ammonia. These figures highlight the need for well-coordinated investment strategies that can attract both domestic and international capital, including public-private partnerships.

Despite the financial challenges, the co-benefits of green ammonia development are substantial. It can dramatically reduce Nigeria's reliance on imported fertilisers, stabilise supply and pricing for farmers, create industrial jobs, and support a cleaner energy system aligned with global climate targets. Additionally, green ammonia exports could become a new revenue stream, enhancing Nigeria's trade balance and international competitiveness in the low-carbon economy.

To realize this vision, the study recommends early implementation of pilot and demonstration plants to test technologies and business models while building local capacity. A coherent national hydrogen strategy is essential to define roles, provide incentives, and coordinate stakeholders. Infrastructure development must be aligned with broader energy and industrial policies, and water use should be optimised to avoid competition with other sectors. Nigeria's strategic coastal location also presents a valuable opportunity for ammonia exports to global markets.

Nigeria4H2 project confirms that Nigeria has the resources and technical feasibility to become a continental leader in the emerging green hydrogen and ammonia economy. By aligning public policy, infrastructure development, and private investment, Nigeria can transform its energy and fertiliser sectors while advancing its climate and development objectives. The success of this transition will not only support national priorities but also place Nigeria at the forefront of Africa's green industrial revolution.

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APPENDICES: Extended Production Costs Breakdown for Ammonia Production

Costs Component	Share of total production cost				
	2025	2030	2040	2050	2060
Utilities	20%	22%	22%	25%	20%
Natural gas	14%	17%	21%	32%	35%
Fixed OPEX	9%	10%	11%	17%	18%
Annualized CAPEX (SMR-HB)	57%	52%	46%	26%	27%

Production costs breakdown for grey ammonia in Nigeria

Costs Component	Share of total production cost				
	2025	2030	2040	2050	2060
Utilities	4%	4%	8%	8%	7%
Natural gas	87%	86%	70%	69%	69%
Fixed OPEX	1%	2%	4%	4%	4%
Annualized CAPEX (SMR-HB)	7%	8%	18%	19%	20%

Production costs breakdown for green ammonia via hydropower and AWE with the optimistic cost progression of green hydrogen

Costs Component	Share of total production cost				
	2025	2030	2040	2050	2060
Utilities	3%	2%	7%	7%	6%
Natural gas	90%	88%	75%	73%	73%
Fixed OPEX	1%	1%	3%	3%	4%
Annualized CAPEX (SMR-HB)	6%	7%	15%	17%	17%

Production costs breakdown for green ammonia via hydropower and PEM with the optimistic cost progression of green hydrogen

Costs Component	Share of total production cost				
	2025	2030	2040	2050	2060
Utilities	1%	2%	3%	3%	3%
Natural gas	93%	86%	81%	79%	76%
Fixed OPEX	1%	2%	2%	3%	3%
Annualized CAPEX (SMR-HB)	5%	10%	10%	19%	17%

Production costs breakdown for green ammonia via solar energy and AWE with the optimistic cost progression of green hydrogen

Costs Component	Share of total production cost				
	2025	2030	2040	2050	2060
Utilities	1%	2%	2%	3%	3%
Natural gas	95%	89%	85%	82%	77%
Fixed OPEX	1%	2%	2%	3%	3%
Annualized CAPEX (SMR-HB)	4%	8%	10%	13%	17%

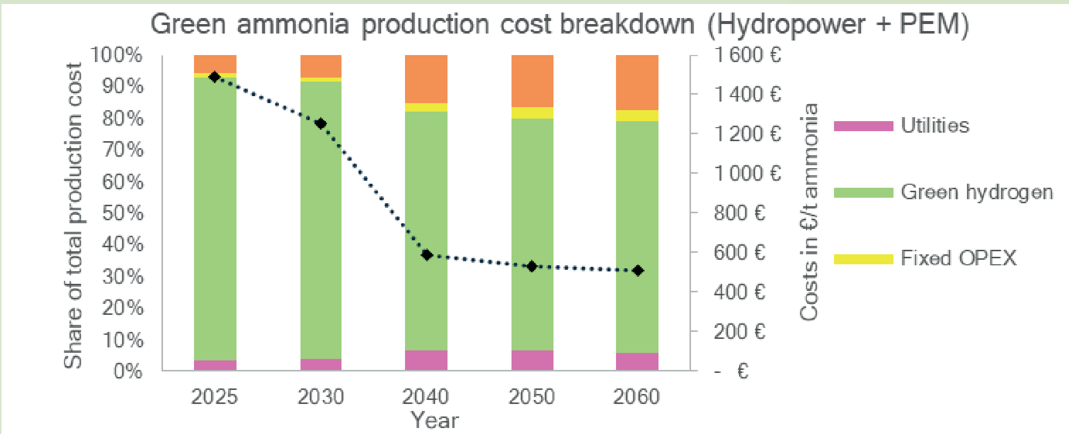
Production costs breakdown for green ammonia via solar energy and PEM with the optimistic cost progression of green hydrogen

Costs Component	Share of total production cost				
	2025	2030	2040	2050	2060
Utilities	2%	4%	4%	4%	4%
Natural gas	95%	89%	87%	85%	84%
Fixed OPEX	1%	1%	2%	2%	2%
Annualized CAPEX (SMR-HB)	3%	6%	8%	9%	10%

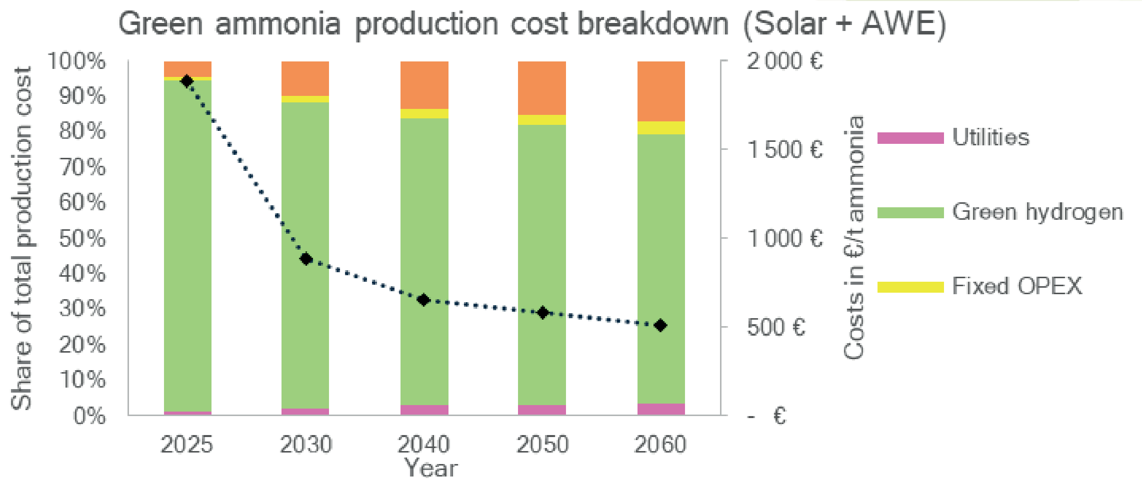
Production costs breakdown for green ammonia via wind energy and AWE with the optimistic cost progression of green hydrogen

Costs Component	Share of total production cost				
	2025	2030	2040	2050	2060
Utilities	2%	3%	3%	4%	4%
Natural gas	96%	91%	90%	87%	85%
Fixed OPEX	0.4%	1%	1%	2%	2%
Annualized CAPEX (SMR-HB)	2%	5%	6%	8%	10%

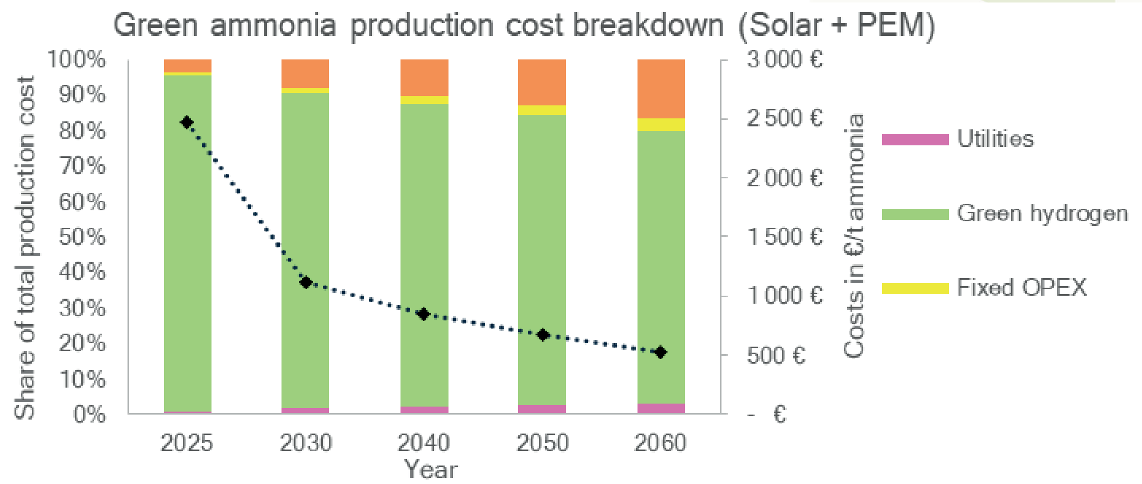
Production costs breakdown for green ammonia via wind energy and PEM with the optimistic cost progression of green hydrogen



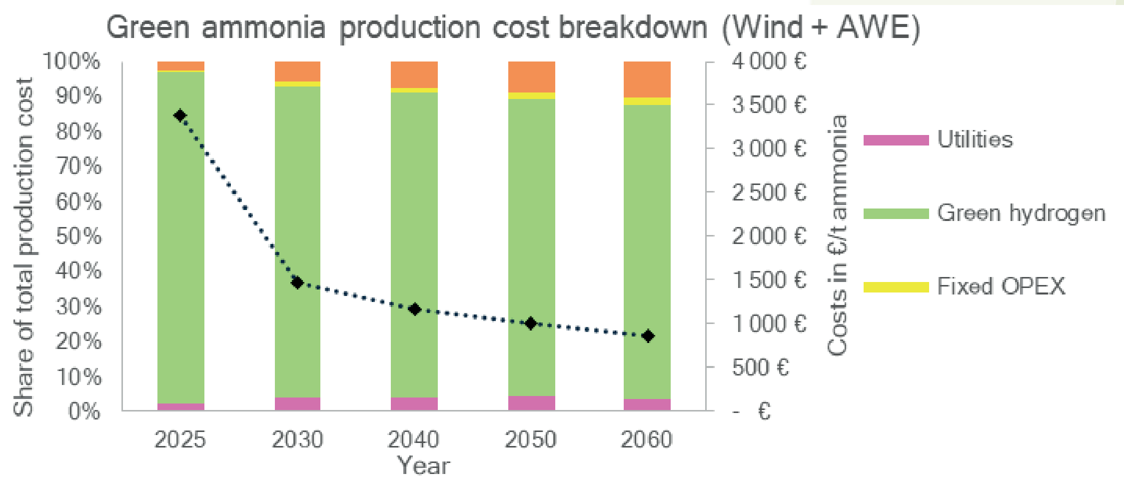
Production costs breakdown for green ammonia via hydropower and PEM with the optimistic cost progression of green hydrogen



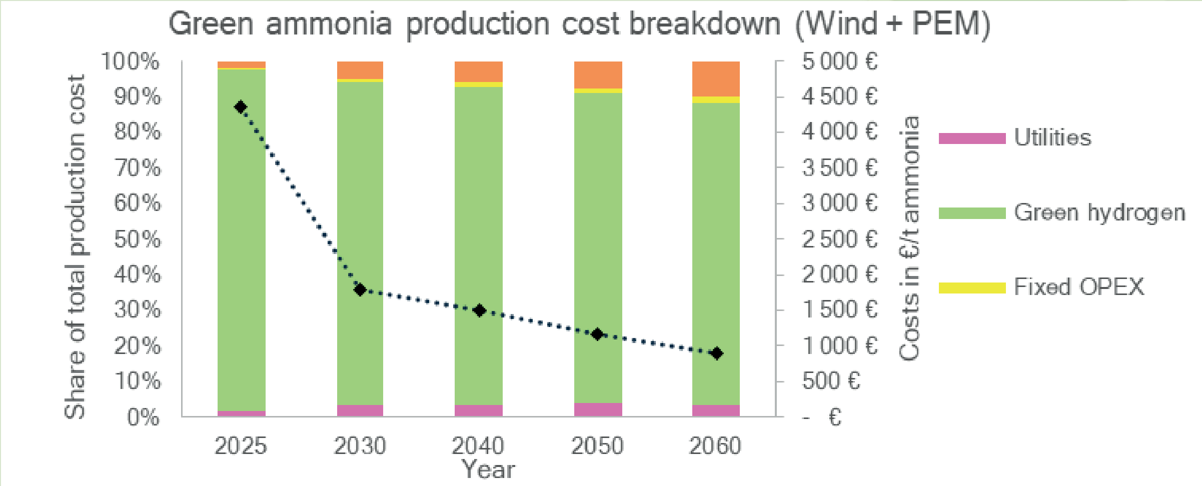
Production costs breakdown for green ammonia via wind energy and AWE with the optimistic cost progression of green hydrogen



Production costs breakdown for green ammonia via wind energy and PEM with the optimistic cost progression of green hydrogen



Production costs breakdown for green ammonia via wind energy and AWE with the optimistic cost progression of green hydrogen



Production costs breakdown for green ammonia via wind energy and PEM with the optimistic cost progression of green hydrogen

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A critical analysis of the Potentials, infrastructure and other enabling framework conditions for Green Hydrogen-to-fertiliser production in Nigeria