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REVIEW

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A review of power-to-X and its prospects for integration in Nigeria's energy transition plan

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Abstract

Nigeria currently relies on 80% thermal energy generation. However, studies have shown that less than 60% of the population have access to power. To address this issue, Nigeria has developed an energy transition plan to achieve net-zero emissions by utilizing eco-friendly and sustainable renewable energy sources. However, the effectiveness of renewable energy resources is often hampered by seasonal variations, which limit the amount of energy that can be produced to meet growing demand. One effective solution to this challenge is long-term energy storage, particularly during periods of low demand. Power-to-X (PtX) technology offers a promising approach by enabling long-term sustainable energy generation and storage for future use when renewable energy availability decreases during peak demands. This study critically reviews the latest advancements in renewable PtX technology and evaluates its potential application within Nigeria's energy sector. Furthermore, it explores the potential obstacles to the widespread adoption of PtX technology in Nigeria. Despite Nigeria's significant potential for implementing PtX initiatives, the country currently falls behind in technology deployment and viable production pathways for sustainable PtX implementation. This shortfall is primarily due to lack of policies, frameworks, and financing schemes to support infrastructural development, especially for long-term energy storage. Given the intermittent nature of renewable energy, a transition strategy that includes adequate storage capacity is crucial. Although green hydrogen, a key component of PtX, has substantial potential as an energy carrier in Nigeria, its immediate use is limited by high production costs. Nonetheless, ongoing efforts to diversify Nigeria's energy mix through infrastructure and policy developments could eventually establish a roadmap for PtX implementation, promoting long-term energy sustainability and distribution efficiency.

Keywords Energy transition plan, Renewable energy, Power-to-X, Hydrogen, Energy storage

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Introduction

The increasing impact of global warming has become a significant problem that must be addressed to achieve a sustainable economy and safe environment. Over the years, there has been a notable and concerning rise in the Earth's average temperature. According to data sourced from the National Oceanic and Atmospheric Administration (NOAA), the Earth's temperature averages around 57 degrees Fahrenheit (Stein & Sharp, 2023), with 2020 registering as the second-warmest year on record. This trend implies that there is an urgent need to address climate change and its profound implications for our planet's well-being while ensuring sufficient energy access to meet up with the growing global population. It is a known fact that industrialization and human activity contributes to climate change, resulting in intermittent change on the global sustainability backdrop (Luthra et al., 2015). Fossil based energy utilization has been the major contributor of greenhouse gas (GHG) emissions resulting to about 5.3% year on year increase (IEA, 2023). This challenge has instigated global attention within the private and public sectors with a growing focus to reach net zero emission. Policy makers have conclusively reached a decision on accelerating the adoption of clean and sustainable energy sources and to ensure the smooth transition to renewables.

To effectively manage the use of these renewable energy sources, it is essential to develop systems capable of storing the energy that had been generated. Currently, there are two main categories of energy storage pathways: short-term and long-term storage systems. Short-term storage pathways are characterized by their high efficiencies and short discharge durations, typically around 24 h (Sterner & Specht, 2021). However, they have high capital cost and low energy density. Examples of such systems include batteries and capacitors. These systems are well-suited for applications requiring quick energy release but are less efficient for addressing long-term energy storage needs. In contrast, long-term energy storage pathways offer lower costs and higher energy densities, making them more suitable for addressing the seasonal fluctuations associated with solar and wind energy.

Despite possessing substantial energy resources, Nigeria, Africa's most populous nation continues to struggle with inadequate energy access and environmental degradation, primarily due to its heavy reliance on fossil fuel. This dependence has led to numerous economic challenges, exacerbated by inadequate infrastructure maintenance. To enhance energy access, Nigeria must explore sustainable solutions for long-term energy storage, supported by robust maintenance systems that ensure the reliability of these storage facilities. One emerging and promising technology in this area is PtX, which offers potential solutions to several critical challenges. This paper delves into PtX technology as a key strategy for addressing these issues.

In this paper, a review of the developments in PtX technology and its potential application within the Nigerian energy sector is studied. In addition, the challenges that might impede the adoption of PtX technology and its future prospects in Nigeria is looked at and then a recommendation aimed at engaging both private and public sectors, as well as investors within the country is provided. Section "Nigeria's power sector and the transition plan" provides a background description of the Nigeria's energy sector, Section "Power-to-X technologies" provides an extensive description of PtX as well as the different energy pathways, Section "Green hydrogen in Nigeria" provides a detailed description of Nigeria's renewable energy potential needed for prospecting PtX initiatives as well as the implementation pathways.

Nigeria's power sector and the transition plan

Currently, Nigeria's power generation is made up of about 80% natural gas and 20% hydropower (Energypedia, 2022). The electricity sector constitutes a centralized systems which includes generation, transmission and distribution. The first ever generation plant in Nigeria was built in 1896, which comprised a 30 kW, 1000v, 80cycle single phase supply generated from coal. However, when crude oil began to be explored and the population of the country began to increase, there was need to increase power generation outcome. In the 1990s, the power supply was insufficient to meet the growing energy demand. As a result, the National Electric Policy was developed. By the year 2000, the National Electric Power Authority (NEPA) was established to manage the generation, transmission and distribution of power in the country. However, the country experienced continuous lack of electricity supply due to the poor and inefficient nature of management by NEPA. Hence the Independent Power Producers (IPP) and the National Integrated Power Projects (NIPP) was established (Babatunde & Shuaibu, 2011). In addition, to ensure efficient implementation of regulatory framework, the Nigerian Electricity Regulatory Commission was established. The Power Holding Company of Nigeria (PHCN) was formed as a transitional body under the Electric Power Sector Reform (EPSR) act that comprised of six generation companies, one transmission company, and 11 distribution companies responsible for the management of the entire power supply chain (Energypedia, 2022). The installed capacity was at 6656.40 MW, but less than 4000 MW was generated. Today, there are 23 power generation plants in Nigeria according to the Nigerian Electricity Regulatory Commission (NERC) with a total installed capacity of 11,165.4 MW and an available capacity of 7,139.6 MW. These plants are predominantly managed by GENCOs, independent power providers and Niger Delta Holding Company. However, with the development in power supply chain, challenges in electricity stability in the country cuts across criticalities in generation capacity, grid stability, and energy storage and distribution efficiencies. This is why there is a need to establish frameworks for renewable energy sources and also policy roadmaps that supports long term electricity storage. Table 1 presents a list of some of the generation companies in Nigeria.

Table 1 Power generation plants in Nigeria (Energypedia, 2022)

Company	State	Type	Installed capacity (MW)
Transcorp power	Delta	Gas	972
Geometric power plant	Abia	Gas	188
Egbin power plant	Lagos	Gas	1320
Geregu power plant	Kogi	Gas	414
Afam power plant	Rivers	Gas	776
Olorunsogo power plant	Ogun	Gas	754
Sapele power plant	Delta	Gas	1020
Omotosho power plant	Ondo	Gas	500
Alaoji power plant	Abia	Gas	1074
Ibom power plant	Akwa Ibom	Gas	190
Kainji power plant	Niger	Hydro	760
Omoku power plant	Rivers	Gas	150
Okpai power plant	Delta	Gas	480
Jebba power plant	Niger	Hydro	578.4
Shiroro power plant	Niger	Hydro	600
Zungeru power plant	Niger	Hydro	700
Ogoja solar power plant	Cross river	Renewable solar	80 (planned)
Katsina wind farm	Katsina	Renewable solar	10
Abuja power plant	Abuja	Gas	1250

While the transmission company of Nigeria (TCN) is responsible for transmitting the generated power, distribution companies through their various substations are responsible for distribution these power to various households, industries, manufacturing companies and commercial buildings (Adetokun & Muriithi, 2021). There are currently 11 distribution companies in Nigeria, as shown in Fig. 1.

Nigeria remains one of the most underpowered countries in the world (Cosmas et al., 2019). Nigeria been ranked as the most populous country in Africa has an emission per CO_2 capita of 0.6 tons in 2021 ranking 25th globally (Knoema, 2022). With the current energy setbacks, the renewable energy sector in Nigeria is gradually taking shape with the rapid increase in solar energy installations for both individual and commercial purposes. However, while this may be true, there must be a concerted effort by the government to ensure that a strategic framework that will lead to not just rapid transition but also an efficient transition is in place. This is necessary, because, while the transition may be fast, the infrastructure and investment opportunities that supports the transition must be put in place.

In 2021, shortly after Nigeria made a commitment at the COP26 meeting held in Glasgow, the Nigeria Energy Transition Plan (ETP) was developed with the goal of achieving net zero target by 2030. It was extended by the government to 2060 to enable a robust and efficient transition feasibility framework. The objective of this plan is to work towards achieving the carbon neutrality target (ETO, 2022). The ETP framework is intended to cut across five key sectors which includes power, oil and gas, cooking, transport and industry. According to ETP, the power industry accounts for about 48 $MtCO_2$ which is about 31% of the total emissions (Fig. 2).

In 2021, Nigeria generated nearly 26 billion kilowatt-hours (kWh) of electricity and consumed approximately 24.61 billion kWh. This translate to a per capita energy consumption 113 kWh, which is considerably lower when compared to global standards of per capita energy consumption of 3081 kWh (WorldData, 2022). In terms of electricity distribution, rural areas in Nigeria received roughly 26% of the total electricity supply which is considerably insufficient (TradingEconomics, 2023). Despite this relatively modest allocation, access to electricity remains below 60% for the overall population, highlighting significant infrastructure management challenges.

However, Nigeria has taken progressive measures to enhance the country's environmental well-being by exploring renewable energy sources, such as solar and wind. Nigeria has also set an ambitious goal of achieving 30 gigawatts (GW) of on-grid capacity by 2030 (ETO, 2022). Within this target, renewable energy sources, including medium and large hydropower, are projected to account for 45%, equivalent to 13.8 GW. Excluding medium and large hydropower, renewables will constitute 30%, or 9.1 GW, of the total generation capacity, while gas will constitute 25% (Energypedia, 2022).

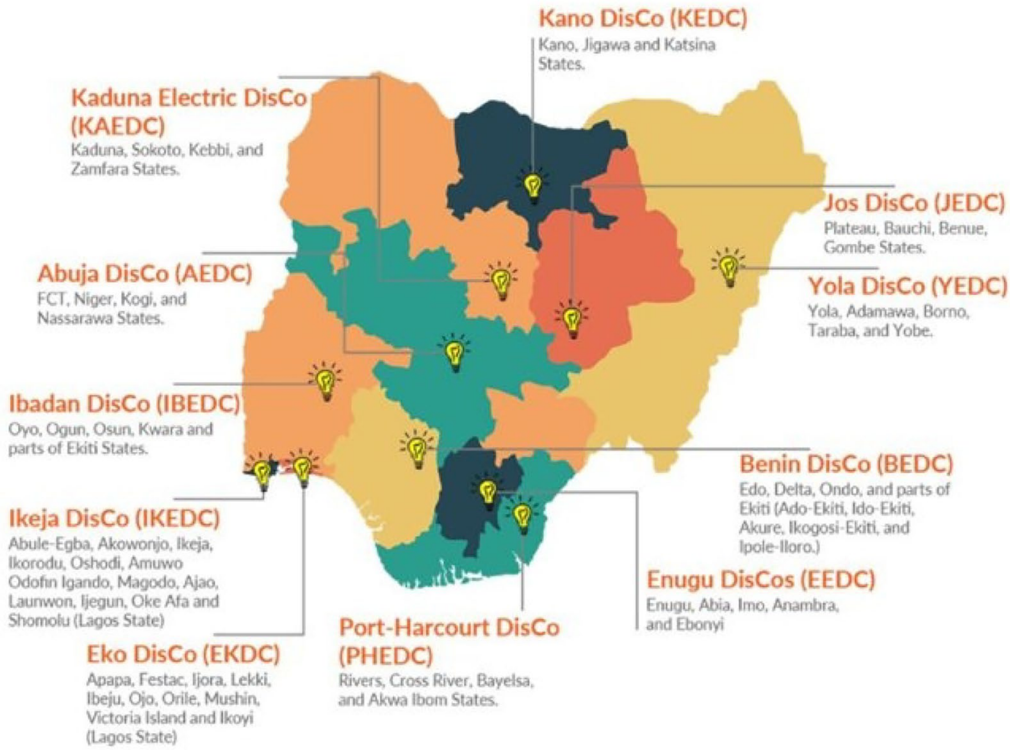

Fig. 1 Power distribution companies in Nigeria (Adetokun & Muriithi, 2021)

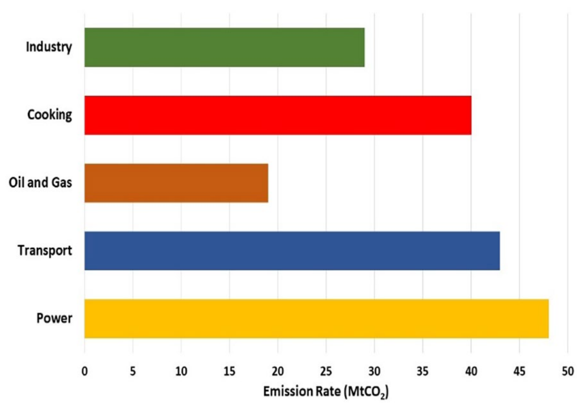

Fig. 2 Nigeria's emission rate by sector (ETO, 2022)

Power-to-X technologies

The concept of power-to-X or for short PtX is a term used to describe the potential of storing excess power generated through renewable means. The concept is considered sustainable, because the excess power that is stored is generated from renewable sources as opposed to the use of fossil fuels or other non-renewable sources (Sternberg & Bardow, 2015). The term "X" typically denotes the specific energy carriers utilized to store surplus power (Rego de Vasconcelos & Lavoie, 2019). In a clear illustration, as depicted in Fig. 3, the surplus electricity generated from renewable sources like wind or solar undergoes a transformation into different energy carriers (referred to as "X"). This process involves combining atmospheric CO_2 capture with hydrogen generated via water electrolysis to form synthetic fuels. These energy carriers can subsequently be stored and converted back into electricity or other energy forms when required. As a result, the term "X" represents these energy carriers and routes produced from renewable energy source, which may encompass synthetic gases (e.g., methane), liquids (e.g., diesel, gasoline), and chemicals (e.g., aldehydes). The concept of PtX was first mentioned by a Japanese scientist named Koji Hashimoto back in 1994 which was used to produce synthetic methane (Ince et al., 2021).

The idea behind this technology is to develop a framework that supports long term energy storage during low demands through conversion to other products known as synthetic fuels (Hermesmann et al., 2021). When peak demands are reached, these fuels can be converted back to electricity. Hydrogen forms the basis for PtX, although methane gas may be suitable as well. Similarly, the storage parameters for PtX encompasses the capacity of storage, duration of storage, topography

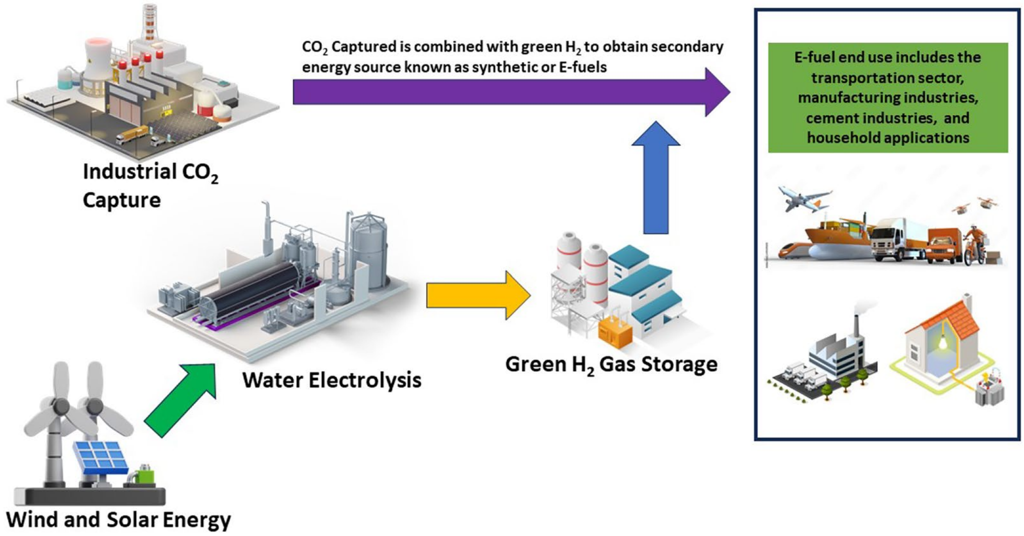

Fig. 3 Framework of power-to-X

of the renewable energy power source and the level of decentralization (Buffo et al., 2019).

Power-to-gas

The derivatives of power-to-gas (PtG) technology is the synthetic or green methane gas which is alternatively called substitute natural gas (SNG) obtained from methanation process (Götz et al., 2016). One of the most common pathways for methanation is the Sabatier process which is based on the catalytic hydrogenation of CO_2 (Schiebahn et al., 2015). This process occurs at a temperature of 250–400 ℃ and pressure of about 80 bar (Hoekman et al., 2010). The hydrogenation process is considered as a combination of the carbon monoxide hydrogenation and reverse water–gas shift reaction:

$$CO_{2(g)} + 4H_{2(g)} \leftrightarrow CH_{4(g)} + 2H_2O_{(g)} \Delta H_r^o = -165.1kJ/mol \tag{1}$$

$$CO_{(g)} + 3H_{2(g)} \leftrightarrow CH_{4(g)} + H_2O_{(g)} \Delta H_r^o = -206.3kJ/mol \tag{2}$$

$$CO_{2(g)} + H_{2(g)} \leftrightarrow CO_{(g)} + H_2O_{(g)} \Delta H_r^o = +41.2kJ/mol \tag{3}$$

$$2CO_{(g)} \leftrightarrow C_{(s)} + CO_{2(g)} \Delta H_r^o = -172.5kJ/mol \tag{4}$$

Equations (1) and (2) indicate the reversible hydrogenation reaction which is accompanied by the reversible water gas shift reaction in Eq. (3) and boudouard reaction in Eq. (4). This reaction is highly exothermic which is why the highest conversion of CO_2 is achieved at a low temperature. Different catalyst materials such as Ni, Ru, and Rh are used during the methanation process, but in most cases, Ni is preferred due to its high reaction activity and cost-effective price (Mills & Steffgen, 1974; Vannice, 1977).

Another process chain in the PtG technology is the biological methanation (BM). In this case, microorganisms serve as the bio-catalysts. The reaction of H_2 and CO_2 is directly done through this organism which obtain their energy through anaerobic metabolism (Pavlostathis & Giraldo-Gomez, 1991). This green methane produced is used to replace fossil-based methane in the generation of household heating, electricity, making clean chemical as well as fuel in the transportation sector (Gordon, 1990).

Hydrogen

Hydrogen serves as the primary element for excess renewable energy storage, and the process of producing hydrogen holds a significance in evaluating the sustainability of renewable energy carriers as an alternative source. Hydrogen has garnered attention as a potential replacement for fossil fuels because of its eco-friendly characteristics and impressive energy potential (Kargbo et al., 2021). Despite being the most prevalent element on Earth, it is rarely found in its isolated form due to its highly reactive nature. Presently, about 50% of the world's hydrogen is generated from fossil fuels and natural gas using a method known as steam methane reforming or for short SMR (Chan et al., 2019; Han et al., 2011; Holladay et al., 2009), and they are commonly nicknamed grey or black and blue hydrogen, respectively. Despite the cheapest commercial method of hydrogen production, it releases a considerable large amount of CO_2. About 9 ton of CO_2 is generated for every 1 ton of grey H_2 that is produced using the SMR method (Ali et al., 2021). As a result, there are interest to improve the efficiency of SMR process through advanced technology integration, such as amin solvents, adsorbents and membrane technology (Rubin et al., 2012; Songolzadeh et al., 2014; Wilberforce et al., 2019). This advanced integration, however, are known to be capital intensive with sophisticated operating requirements.

Water electrolysis is the cleanest method of hydrogen production. It is referred to as green hydrogen, because it is produced from sustainable source. Water electrolysis typically involves the use electricity obtained from solar and wind to split water molecules into hydrogen and oxygen. However, even with the sustainability of hydrogen production from water electrolysis, only 4% of the total global hydrogen is produced from it (Irena, 2022). Despite's hydrogen prospects in PtX, there are certain criticalities that needs to be addressed to maximize the efficiency of PtX technology. Apart from its high production cost, hydrogen has a very low volumetric density at atmospheric temperature and pressure. This means that it requires a substantially large storage space to be stored. Similarly, the difficulties associated with its transportation and corrosion tendencies makes it very difficult to manage. Thus, techno economic feasibility and environmental safety assessment associated with the logistical supply chain of hydrogen are crucial. The production and storage solution should encompass lightweight features to aid easy transportation, low production cost and efficient recyclability for filling and discharging phase (Dutta, 2014).

Within the concept of power-to-hydrogen, surplus electricity generated from renewable sources like wind or solar energy is harnessed for storage by means of electrolysis, which typically operates at an efficiency rate of around 85% (Glenk & Reichelstein, 2019). The stored hydrogen which is then reacted with CO_2 captured from the atmosphere can subsequently be used for producing various energy carriers, including synthetic fuels. This technology is often used as a variable renewable energy (VRE) source especially when there are fluctuations in power generation efficiency.

Electrolysis of water

Green hydrogen is produced from water electrolysis process and it is the cleanest method using renewable energy sources (Wanner, 2021). Though this method is initially implemented in small scale electrochemical process, the large commercial scale production is typically the power-to-X technique. Water is separated into hydrogen and oxygen molecules by direct electricity from renewable source. As shown in Fig. 4, the process typically requires an electrolytic cell which combines oxidation and reduction to separate hydrogen from oxygen (Kelly, 2014). The electrolytic cells are made of two electrodes, the anode and cathode which are chosen based on the kind of electrolytes used. The efficiency of the electrolytic process is improved using an electrolyzer which acts as a membrane between the electrode and water molecules (Lim et al., 2014). In general, electrolyzers are divided into three categories based on the type of electrolytes used on them (Mohammadi & Mehrpooya, 2018). This includes the proton exchange membrane (PEM), solid oxide electrolyzers (SOEC) and the alkaline electrolyzers. Each of this electrolyzers are efficient in their own ways, but also pose their own setbacks and limitations.

The PEM electrolyzer is well-known for its compact design due to its solid polymer electrolytes. In addition, it does not suffer from leakages due to the solidity of the electrolyte. However, the major setbacks of the PEM are that it requires a specific material that operate under high voltage in an acidic interface (ECP, 2022). The alkaline electrolyzer is made up of about 30% electrolyte (Sorensen, 2012). It is the commonly used and matured commercial electrolyzer due to its low capital cost (Ursua et al., 2012). However, in contrast to the PEM,

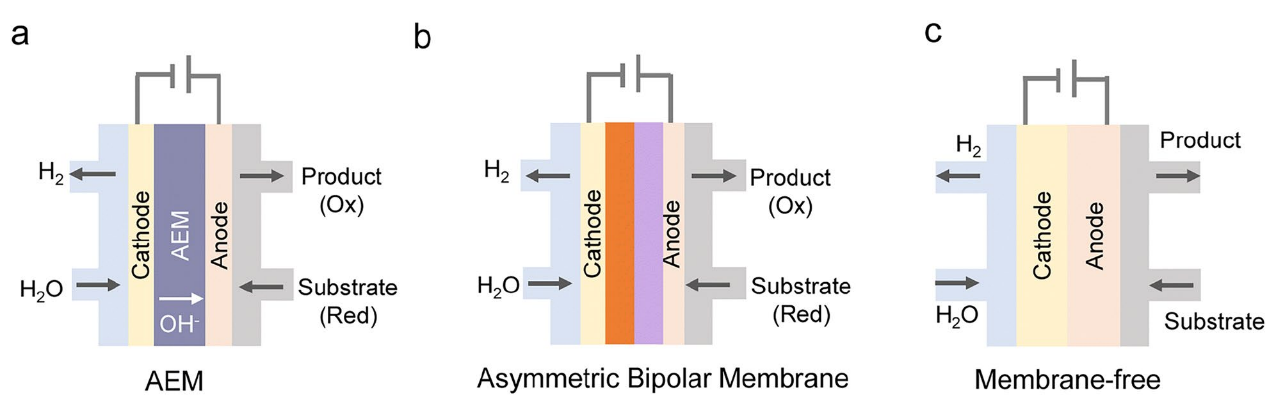

Fig. 4 Water electrolysis process for each electrolyzers (Yao et al., 2023)

the liquid nature of the electrolyte most likely leads to leaking issues. In addition, its performance deteriorates under part load. The SOEC is relatively a new method which operates at a high temperature. The advantage of this electrolyzer is that it benefits from solid electrolytes thereby eliminating the tendencies of leakage. In addition, its compact design reduces ohmic loss; however, it is shown that its drawback is mostly revolved on its long-term degradation (Mohammadi & Mehrpooya, 2018). Electrocatalytic water splitting has shown to be efficient for hydrogen production; however, the issue of high energy consumption must be addressed to ensure a large-scale industrial use of it for hydrogen production (Yao et al., 2023). Table 2 presents a summary description of the three electrolyzers used for water electrolysis.

Power-to-liquid and chemicals

Liquid fuels such as jet fuels, diesel, gasoline and chemicals gotten from power-to-liquid (PtL) technology have become another alternative to fossil-based energy. Currently, there is no concrete proof of concept for power-to-jet fuel technology. Nevertheless, it has the potential to be blended up to 50% with synthetic paraffinic kerosene generated from power-to-liquid (PtL) processes, thereby reducing carbon emissions within the aviation sector (Schmidt et al., 2018). Regarding gasoline production, while it typically originates from the refining process, it is also possible to create long-chain hydrocarbons from synthetic or clean gas using the renewable Fischer–Tropsch (FT) process. FT synthesis yields a variety of hydrocarbon suitable for use as transportation fuel and chemical feedstock. This process involves catalytic reactions, with operating conditions designed to maximize the production of higher molecular weight hydrocarbons (Wentrup et al., 2022). Furthermore, the FT synthesis process may entail side reactions, including the water gas shift reaction. It is categorized into low and high-temperature FT synthesis, as shown in Fig. 5. The products of this process also include valuable desirable chemicals such as olefins, paraffins and alcohol as well as smaller products such as aldehydes. Acids, ketones and carbon (NETL, 2023).

Another production pathway for the production of synthetic fuels is the methanol intermediary. The approach can leverage well-established industrial processes that have been utilized for many years in diverse large-scale applications. These processes include natural gas reforming and methanol synthesis, which have even

Table 2 Common electrolyzers and their properties (Buttler & Spliethoff, 2018; Sapountzi et al., 2017)

Electrolyzer	Electrolyte	Cell Voltage	Temp (℃)	Max Pressure (bar)	Power consumption (kWh/m^{3}H$_2$)	System Lifetime	Efficiency (%)
PEM	Solid Polymer	1.8–2.2	< 150	400	4.4–7.1	10–20	68–82
SOEC	Stabilized zirconium oxide	–	> 500	30	3.7	20	80–100
Alkaline	NaOH, KOH	1.8–2.4	< 100	690	3.8–8.2	20–30	59–79

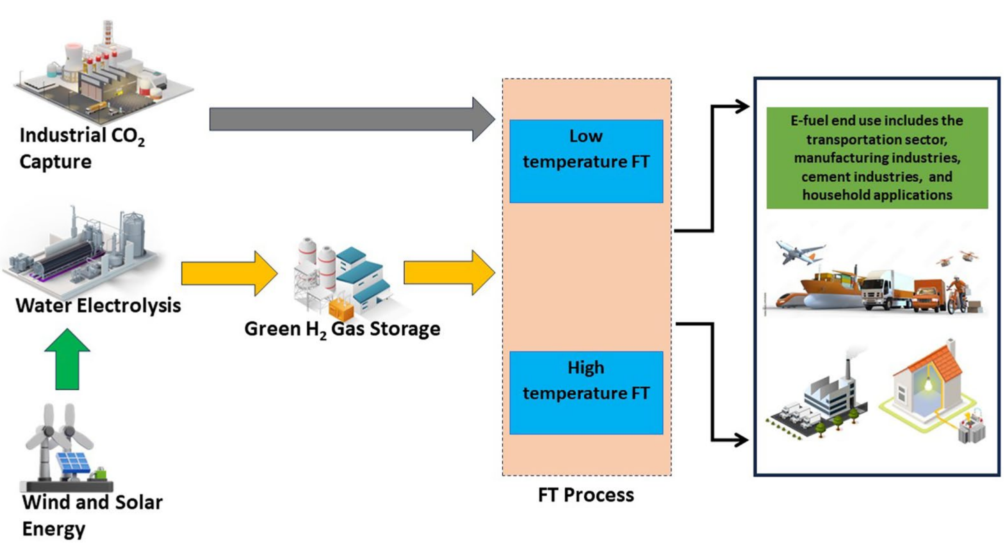

Fig. 5 Fischer–Tropsch process-based PtX

seen applications like methanol-to-gasoline conversion in certain instances (Schmidt & Roth, 2016). Table 3 presents some comprehensive overview of research activities within the scope of PtX technology and progress done in different countries. The table provides insights into the technological capacity and implementation timelines of PtX projects. While several progresses have been made in PtX, most of them are small or pilot scale. Notably, Egypt and South Africa have emerged as frontrunners among African nations, showcasing significant advancements in PtX technology research and making substantial progress towards full-scale implementation.

Green hydrogen in Nigeria

The hydrogen sector in Nigeria remains in its early stage, despite the introduction of ETP initiatives. African nations such as Angola, South Africa, and Namibia have announced ambitious large-scale hydrogen projects in collaboration with Germany. Germany, Europe's largest economy, has taken on a pivotal role in propelling hydrogen technology forward within the African context. Their overarching goal is to create a hydrogen flagship initiative that not only fosters sustainability but also acts as a catalyst for the expansion of hydrogen market throughout the continent (Mammoser, 2022). As illustrated in Fig. 6, Nigeria boasts substantial potential for green hydrogen production, amounting to 6271 TWh/a, ranking behind only Niger and Mali in the region. Furthermore, the entire West African region exhibits remarkable capabilities, with the potential to generate approximately 115,940 TWh of green hydrogen annually, without encountering any significant water constraints due to electrolysis. However, there is a need to establish a strategic framework that could help harness these potentials if Nigeria is to be one of the major players in the green hydrogen sector.

In 2022, Nigeria imported hydrogen valued at $14.2 million, primarily from China, the United Arab Emirates (UAE), Singapore, Italy, and India, with China being the leading supplier (OEC, 2023). The predominant type of hydrogen imported is blue hydrogen, accounting for over 90% of the total hydrogen utilized in Nigeria. The cost of blue hydrogen ranges between $2.8 per kg and $3.5 per kg, in contrast to green hydrogen, which costs between $4 per kg and $17.4 per kg. In Nigeria, while many companies produce and use hydrogen onsite, the majority of power generation companies utilize it primarily for cooling purposes. For instance, Transcorp and Egbin power stations employ hydrogen as a coolant, marking a significant large-scale application of hydrogen in the country. In addition, hydrogen is crucial in oil and gas refineries for processes such as hydrotreatment, hydrocracking, and ammonia production, the latter being essential for fertilizer manufacturing. The Dangote manufacturing plant, for instance, uses hydrogen extensively in its production processes. On a smaller scale, hydrogen finds applications in pharmaceuticals and food preservation.

Power-to-X integration in Nigeria

Nigeria's green economy space is rapidly expanding. With consistent effort by the government to usher in a sustainable paradigm for energy generation and utilization, the country is ready to overcome the persisting backdrop of energy supply. Firstly, it is essential to consider the types of technologies for PtX that align with Nigeria's energy resources. A primary technology selection is the type of electrolyzer used, as this will significantly impact the efficiency and cost-effectiveness of PtX projects (Robinius et al., 2018). In addition, both capital expenditure (Capex) and operating expenditure (Opex) are crucial factors in assessing the financial implications of these projects. Other critical technology selection criteria include; Power Conversion Efficiency, technical Maturity, guarantees, bankability, and availability of Production Capacity. In the context of Nigeria, establishing a proper framework to support these technology selections is essential. As a way to enhance the technology landscape, Nigeria planned in 2022 to invest approximately 924 billion naira (around 2 billion USD using 2022 exchange rate) through a public–private-development partnership (Jaiyeola, 2022). This investment includes collaborating with states to establish pilot technology incubation centres, which aim to strengthen technological development and innovation within the country. Also to ensure a smooth integration of PtX technology into Nigeria's energy framework, there must be a compatibility test of existing infrastructures such as power grids and gas pipelines, to boost the power distribution efficiency. The country has abundant renewable energy resources, particularly in solar and wind, which can be harnessed by developing large-scale solar and wind farms and implementing hybrid renewable energy systems. Nigeria's vast natural gas reserves provide an opportunity for blue hydrogen production, and investing in carbon capture and storage (CCS) technologies can reduce emissions from this process. The existing energy infrastructure, including pipelines, refineries, and power plants, can be upgraded and repurposed for PtX applications, such as installing electrolyzers to produce hydrogen during off-peak hours. Government initiatives and policies, like the Energy Transition Plan (ETP), can further support PtX technologies by fostering public–private partnerships. In addition, Nigeria's growing workforce can be trained in PtX technologies through dedicated training programs and educational initiatives.

Table 3 Some past and ongoing PtX studies reported (Dahiru et al., 2022)

Category	Location	Commencement Years	Electrolyzer	Capacity	Conversion Efficiency	Source
PtG	South Korea	2020	PEM, Alkaline	1000ton/day	76.7	Choe et al., (2021)
PtG	Spain	2020	AEL	22.4m^3/s	–	Gutiérrez-Martín et al., (2020)
PtG	Germany	2018	PEM	90 MW Electrolyzer	72.7	Chauvy et al., (2020)
PtG	Italy	2018	Alkaline	8500Nm^3/hr	52.1% with CCS	Bassano et al., (2020)
PtG	North Sea	2018	PEM	50 MW electrolyzer	40%	Crivellari and Cozzani, (2020)
PtG	Western Europe	2017	PEM	6ton/hr of H_2	69%	Sarić et al., (2017)
PtG	Germany	2017	SOEC	2500KW	40%	(Leonzio, (2017)
PtG	USA	2016	SOEC	50 MW electrolysis stack	81.1	Reznicek and Braun (2020)
PtG	South Africa	2016	Alkaline	760Nm^3/hr	-	Chiuta et al., (2016)
PtG	Germany Switzerland	2015	PEM	10 MW	80%	Hassan et al., (2019)
PtG	Finland Denmark	2015	PEM Alkaline	500m^3/day	70%	Pääkkönen et al., (2018)
PtG	France	2015	Alkaline	230m^3/hr	–	Collet et al., (2017)
PtG	Germany	2014	–	13.2 MW	81%	Peters et al., (2019)
PtG	USA	2009	–	40,000 kg/day of H_2	78.1%	Becker et al., (2019)
PtG	Ireland	2020	–	125m^3/h	76.7%	Vo et al., (2017)
PtG	2021	Greece	AEL	500,000 ton/yr	75%	Ipsakis et al., (2021)
PtG	2020, 2030 and 2040	Ireland	PEM	10 MW Electrolyzer	52.2%, 55.8% and 59%	McDonagh et al., (2018)
PtG	2030	Switzerland and Germany	AEL	10 MW Electrolyzer	75%	Gorre et al., (2020)
PtG	2030–2050	United Arab Emirate	AEL, SOEC	–	54.7% AEL and 63.7% SOEC	Eveloy and Gebreegziabher, (2019)
PtG	2050	Germany	SOEC	1289 ton/annum	77%	Salomone et al., (2019)
PtL	Germany, Nordic and Baltic Countries	2050	PEM	20.1 million ton/Anum	71%	Ikäheimo et al., (2018)
PtL	USA	2030	Alkaline	100 ton/day	90%	Jouny et al., (2018)
PtL	Indonesia	2030	Alkaline	13000ton/yr	7.9%	Fernando and Purwanto, (2021)
PtL	Germany	2030	Alkaline PEM	300ton/day	95%	Nosherwani and Neto, (2021)
PtL	Argentina Chille	2020	Alkaline	–	70% electrolyzer efficiency	Armijo and Philibert, (2020)
PtL	USA	2020	Alkaline	20,000ton	78%	Lin et al., (2020)
PtL	USA	2019	PEM SOEC	140ton/day	80%	Gomez et al., (2020)
PtL	USA	2018	–	1500ton/day	-	Li et al., (2019)
PtL	China	2017	SOEC	50000ton/anum	75.3%	Zhang et al., (2020)
PtL	North west Europe	2017	–	12000ton/anum	42.3%	Rumayor et al., (2019)
PtL	Spain	2017	–	–	42%	Rumayor et al., (2019a, 2019b)
PtL	USA	–	PEM	40.3ton/annum	12.7%	Palys et al., (2019)
PtL	Southern Europe	2017	Alkaline	300ton/day	–	Sánchez and Martín (2018)
PtL	North west Europe	2016	–	17000ton/yr	98%	Aldaco et al., (2019)
PtL	USA	2030	PEM	159m^3/day	–	Isaacs et al., (2021)

Table 3 (continued)

Category	Location	Commencement Years	Electrolyzer	Capacity	Conversion Efficiency	Source
PtL	Canada	2050	Alkaline PEM	1100ton/day	51%	Adnan and Kibria (2020)
PtL	South Korea	2050	Alkaline PEM SOEC	100ton/day	45.6%	Lee et al., (2021)
PtL	Germany	2030	PEM	–	84.5%	Decker et al., (2019)
PtL	South Korea	2030	–	$3.7*10^5$ton/annum	75.9	Zhang et al., (2019)
PtL	Finland	2019	Alkaline	200 MW	79%	Habermeyer et al., (2021)
PtL	China	2030	PEM	$6*10^5$ton/annum	–	Chen et al., (2019)
PtL	Germany	2030	Alkaline SOEC	133 kg/hr of H_2	71%	Hombach et al., (2019)
PtL	Egypt	2025	Alkaline	100barrel/day of liquid fuel	50%	Trieb et al., (2018)

To effectively integrate PtX into Nigeria's energy framework, comprehensive feasibility studies should be conducted to assess the technical, economic, and environmental aspects of PtX projects. Infrastructure development, including the construction of electrolyzers and storage facilities and the modernization of the national grid, is essential for PtX projects. The government should establish supportive policies and a clear regulatory framework, along with financial mechanisms like investment funds and green bonds, to attract investment. Public awareness campaigns and community engagement are vital to educating stakeholders about the benefits of PtX technologies. Furthermore, establishing innovation hubs and technology incubation centres and partnering with international experts can foster research and development in PtX technologies (Fig. 7).

Renewable energy resources for PtX

The primary renewable energy sources for PtX include solar and wind. These resources are used to generate electricity, which is then converted into green hydrogen and other synthetic fuels or chemicals through electrolysis.

- Solar energy: Solar power is harnessed through photovoltaic (PV) cells and concentrated solar power (CSP) systems. The electricity generated can be used for direct applications or converted into other energy carriers like hydrogen (through electrolysis) or synthetic fuels, which can be stored or used for transportation and industrial processes.
- Wind energy: Wind turbines generate electricity, which is often used for grid supply or can be converted to hydrogen or synthetic gases. Wind energy is ideal for PtX applications in areas with consistent wind patterns, enabling large-scale energy conversion and storage.

Solar energy in Nigeria

Nigeria has the potential to generate about 42GW of power from solar annually which is about 55% energy potential greater than the present gas fired plant generation corresponding to about 258 million barrels of oil that may be used for power generation (Abam et al., 2014). A study suggests that the northern part of the country has greater solar energy potentials compared to any other part of the country (Ogunjo et al., 2021). The country also has an annual average sunshine of about 6 h with 3.5 h at the coastal zones and about 9 h in the northern zones (Abam et al., 2014a). In Fig. 8, the solar radiation map for Nigeria is displayed. The zones on the map are categorized into three distinct regions. Zone I predominantly encompasses states in the north-western and north-eastern regions of Nigeria, boasting the highest solar radiation potential. Zone II encompasses a combination of states from both the northwest and southwest regions. In contrast, Zone III (mostly south–south and southeast) exhibits lower solar radiation potentials.

Table 4 presents the solar energy levels for each region in the country, providing data on the annual average global solar radiation and the annual average solar energy intensity. Notably, zone III which comprise of states in the coastal region are mostly less efficient for off-grid photovoltaic system made up of solar panels, inverters, direct current (DC) loads and set of battery banks. This is practically due to the intermittent nature of the solar radiation levels hence providing a need to store the energy that has been generated. Given Nigeria's abundant solar potential, the country possesses the capability to

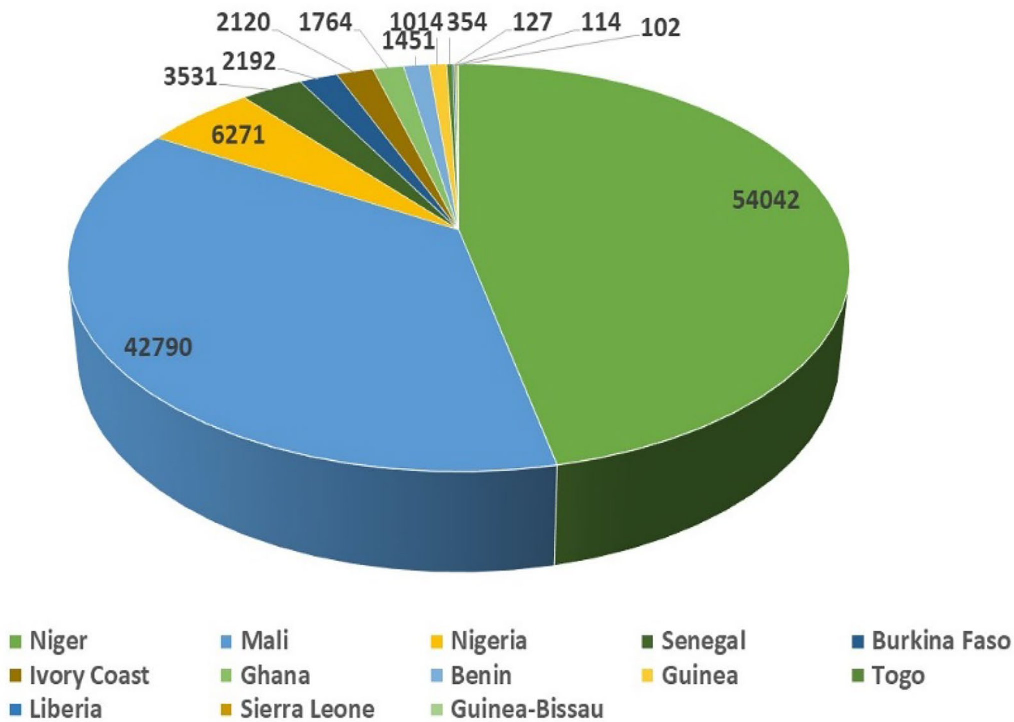

Fig. 6 Green hydrogen potential in West Africa (TWh/a) (Adaramola & Gaiya, 2023)

conduct strategic PtX feasibility studies. With this solar energy potential, it is possible to generate as much hydrogen needed to supply more than 50% of the population in Nigeria for households and commercial use. In addition, it will be possible to reduce power grid breakdowns and enhance energy efficiency in both rural and urban areas across the nation.

Wind energy potential

Wind energy potentials are usually obtained from windmills placed on hills or topographic lands. A study by Ajayi, (2009) found that the peak wind season in the country predominantly falls between April and August. During this period, wind speeds typically range from 1.4 to 3.0 m/s in the southern regions and 4.0 to 5.12 m/s in the hilly northern areas (Fig. 9). Notably, the study highlights the potential for even higher wind speeds, reaching up to 8.70 m/s in the southeastern and north-central regions of the country (Ayodele et al., 2018). This heightened wind velocity is primarily attributed to the expansive land areas characterized by hills and mountainous terrain. Moreover, data obtained by the Nigerian Meteorological Agency (NiMet) revealed that southern and northern states have a mean wind profile ranging between 3.0–3.5 m/s and 4.0–7.5 m/s at 10 m height, respectively (NiMet, 2009). This highlights Nigeria's substantial wind energy potential, which can be utilized for PtX development. In addition, considering the intermittent nature of wind energy, PtX emerges as a viable solution for energy storage during periods of low demand or peak energy generation.

Challenges of PtX adoption in Nigeria

PtX has several imminent challenges globally. Despite the rapid development of the technology, most of the solutions are expensive compared to fossil fuels and notably, this distinct difference can generally be attributed to the costs associated with PtX infrastructure including setting up an industrial scale electrolysis system. This is why majority of PtX solutions are currently small scale. The EU has the highest allocation of funding for PtX research and innovation, but still faces issues of high electricity price, lack of harmonized standards and regulation as well as public acceptance challenges. Likewise in Asia, countries like Japan, China and South Korea have also showed investment interests with a particular emphasis on hydrogen manufacturing. However, they face issues on the Infrastructural establishment and regulations. North America and Oceania have showed tendencies of PtX deployment but lacks policy drivers and market incentives. Africa and Nigeria are also not left behind on this peculiar challenges.

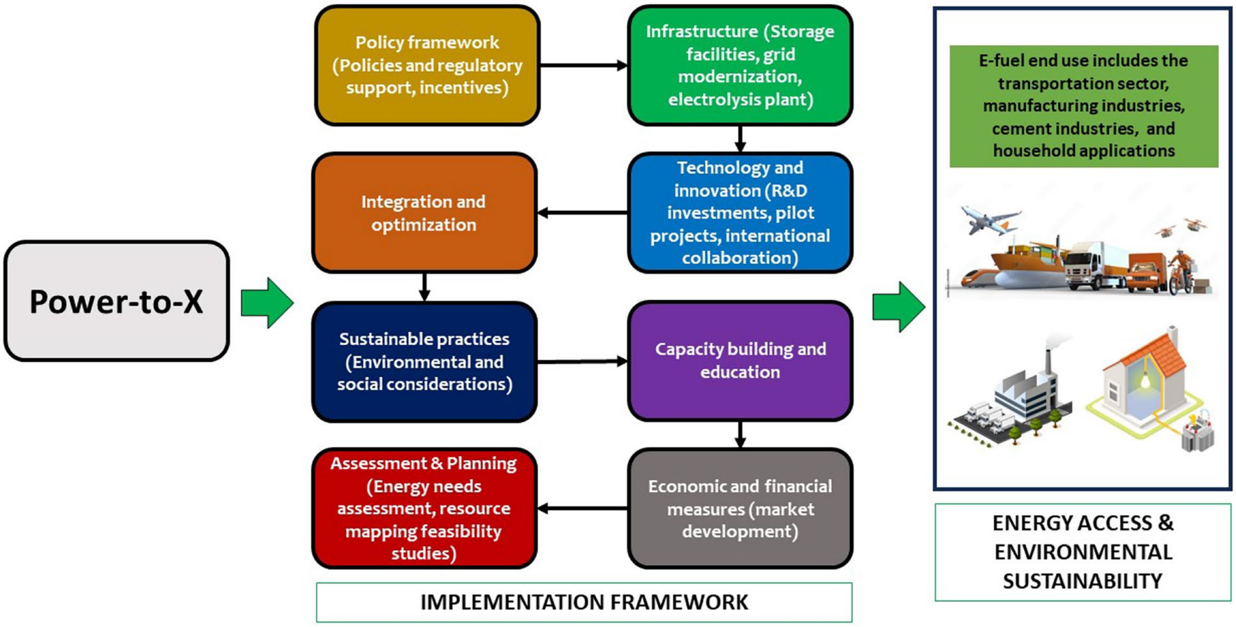

Fig. 7 Application pathways for PtX

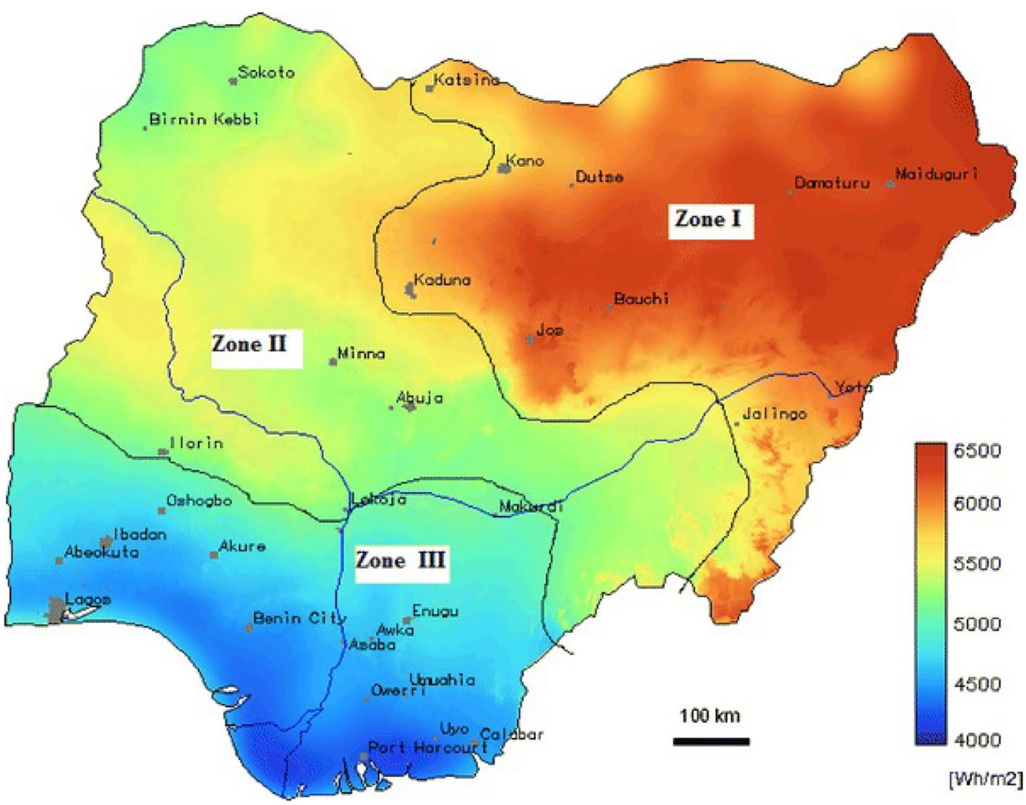

Fig. 8 Solar radiation distribution in Nigeria (Abam et al., 2014)

Lack of technical resources

One of the challenges in PtX is the production and storage of these energy carriers. For instance, Hydrogen gas which is primarily the gas used in producing other synthetic fuels or energy carriers is faced with production and storage issues. At present, hydrogen energy is stored on a physical based (compressed, cryogenic or liquid) or material based (adsorbent, liquid organic, interstitial hydride, complex hydride or chemical hydrogen) system (Züttel, 2003). This storage usually requires a high pressure (usually ranges between 350 and 700) tank for gaseous storage and a cryogenic temperature (usually − 252.8 ℃) for liquid storage (David, 2005). However, hydrogen presents certain challenges when it comes to its storage and utilization. One of the primary issues with hydrogen is its low volumetric energy density. This means that a significant volume of space is required to store a given amount of hydrogen gas, making it less practical for applications where storage space is limited. Furthermore, hydrogen can be quite demanding on storage materials. Its high boiling point, which approaches absolute zero, means that it must be kept at extremely low temperatures to remain in a gaseous state (Niaz et al., 2015). This low-temperature requirement can lead to the embrittlement and cracking of storage materials over time, which poses a considerable challenge for long-term storage solutions.

Nigeria currently lacks the technical capacity for effective hydrogen energy storage. Developing the infrastructure and expertise required for safe and efficient hydrogen storage is a complex endeavour that demands significant investment in research, technology, and education. Addressing these challenges is essential for harnessing the full potential of hydrogen as a clean energy source in Nigeria. As Nigeria continues to invest in its technical capabilities, the prospects for utilizing hydrogen as a sustainable energy option will become increasingly viable.

Lack of financing

PtX requires a significant amount of investment in infrastructure as well as high initial energy costs. This includes costs in production of hydrogen, energy storage as well as costs in transportation. Although this has been a global challenge, Nigeria is not excluded. At present, the country does not clearly have a well-defined investment strategy for PtX. However, as part of the ETP initiatives, Nigeria has envisaged an investment potential of $1.9 trillion in the entire energy landscape to meet up to the 2060 net zero target, with an annual cost of $10 billion (ETO, 2023). In addition, the ETP analysis has indicated that the power sector represents the most substantial allocation of both capital and operational expenditures, totalling a significant $270 billion. This financial commitment will serve as the cornerstone for executing investment initiatives in PtX technologies. In addition to this, it is imperative for the country to establish comprehensive guidelines for cost management, enabling investors to monitor and evaluate their returns on investment.

Lack of policy and regulation

The absence of standardized regulations and guidelines for PtX has been a significant obstacle to its adoption. Nigeria currently lacks a comprehensive policy framework and standards for PtX and the utilization of hydrogen energy (Adaramola & Gaiya, 2023). This deficiency could potentially jeopardize the long-term sustainability of the technology within the country. To effectively embark on energy storage through PtX, Nigeria must establish robust standards and regulations that provide a clear roadmap for the technology's deployment. Furthermore, it's important to recognize that private investors may be hesitant to invest in PtX without the assurance of these essential policies in place. Therefore, developing and implementing these regulatory measures is not only vital for the successful integration of PtX but also for attracting much-needed private sector investments in this innovative energy storage solution.

Future direction

The foundation of the PtX is fundamentally reliant on the accessibility of green hydrogen, enabling the conversion of surplus renewable energy into valuable products

Table 4 Solar energy levels in Nigeria (Abam et al., 2014)

Zone	Duration of sunshine (hr/day)	Annual average solar energy intensity (kWh/m^2/yr)	Annual average global solar radiation (kWh/m^2/day)	States
I	6.0	2186	5.7–6.5	Borno, Yobe, Jigawa, Kano, Kaduna, Bauchi, Gombe, Adamawa, Plateau, Katsina
II	5.5	2006	5.0–5.7	Sokoto, Zamfara, Kebbi, Niger, FCT, Nasarawa, Taraba, Kwara, Benue, Katsina, Some parts of Jos
III	5.0	1822	< 5.0	Lagos, Oyo, Osun, Ekiti, Kogi, Benue, Rivers, Delta, Imo, Anambra, Abia, Enugu, Edo, Ondo, Bayelsa, Akwa-Ibom, Cross-rivers, Ebonyi

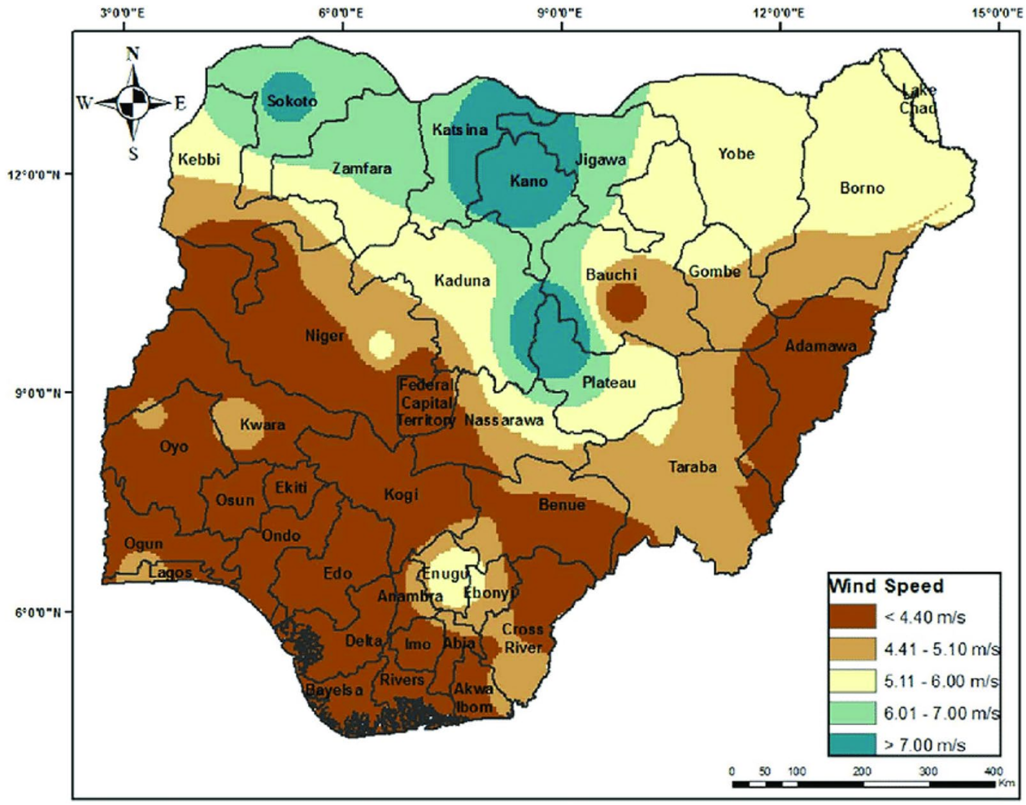

Fig. 9 Nigeria's wind speed map (Ayodele et al., 2018)

such as synthetic fuels, chemicals, and materials. However, while the ETP does incorporate hydrogen as a viable decarbonization option for Nigeria's energy sector, it does not foresee hydrogen playing a substantial role in Nigeria's final energy consumption by 2030 which may impede the possible realization of PtX initiatives. Instead, by 2030 (Adaramola & Gaiya, 2023), hydrogen is expected to contribute a modest share, with significant growth projected from 2030 to 2050, experiencing a Compound Annual Growth Rate (CAGR) of about 21%. This gradual but steady increase underscores the evolving role that hydrogen is likely to play in Nigeria's energy landscape over the coming decades (Adaramola & Gaiya, 2023). To put it differently, the plan envisions a gradual increase in hydrogen production, with a significant ramp-up occurring after 2030. This cautious approach is attributed to market uncertainty. The strategy proposes that both existing and newly established facilities before 2030 could employ Steam Methane Reforming (SMR) to produce hydrogen, complemented by Carbon Capture and Storage (CCS). Meanwhile, facilities constructed after 2030 would have the flexibility to choose between green or blue hydrogen production methods, adapting to the evolving hydrogen market as it matures.

Several initiatives have been undertaken by various stakeholders to mitigate the market uncertainty that has hindered government support and investor engagement in the Nigerian green hydrogen sector. In 2023, an inter-ministerial committee was established with the objective of formulating a comprehensive Nigerian hydrogen policy. Simultaneously, the German–Nigerian Hydrogen Office unveiled a learning focusing on the Policy and Regulation Frameworks essential for the establishment of a hydrogen market in Nigeria (NIPC, 2022). This study was aimed at providing valuable insights for policymakers and advocacy groups dedicated to fostering the growth of a hydrogen market within Nigeria.

Numerous studies are currently exploring different uses of green hydrogen, including smaller-scale systems. One noteworthy study, led by the Delegation of German Industry and Commerce in Nigeria, is examining the possibility of adding a green hydrogen production unit to an existing solar PV mini-grid in Gbamu Gbamu, Ogun State. This project focuses on creating an energy system that uses surplus electricity generated by the solar PV system to make green hydrogen. It does this by carefully optimizing the combination of solar PV panels, electrolyzers, fuel cells, hydrogen storage, and compressors. The analysis from this study shows that the cost of energy is

77 Nigerian Naira per kilowatt-hour (NGN/kWh) which is approximately 0.04 USD/kWh, thanks to the efficient use of excess renewable energy, which makes up 18% of the total electricity generated. In addition, the project explores the possibility of selling the produced hydrogen to heavy-duty vehicles, contributing to the broader goal of reducing emissions in the transportation sector (AHK, 2022). The sensitivity analysis has revealed that as time progresses, the cost of producing hydrogen from the mini-grid decreases and becomes more cost-effective than diesel. Furthermore, there is an ongoing green hydrogen pilot project being conducted in Ondo State.

Conclusion and recommendation

While Nigeria's energy outlook heavily relies on the availability of infrastructure, it is imperative to consider integrated options that can enhance long-term energy availability, such as advanced storage systems. PtX technologies offer advanced and sustainable long-term storage solutions. The following outlines the recommendation that will expedite the implementation of PtX in Nigeria.

1. Policy and regulatory framework: Nigeria needs to create clear rules and regulations for PtX technologies. These guidelines should cover safety, environmental protection, and incentives to encourage their use. For instance, policies initiatives developed for hydrogen by the Nigeria's inter-ministerial committee in 2023 can be extended for PtX technologies since Hydrogen forms the basis of PtX technologies. The German–Nigerian hydrogen office can similarly integrate policy guidelines it developed for hydrogen in establishing a functional PtX market in Nigeria (NIPC, 2022). Implementing these guidelines could aid attracting investment opportunities as well as foster effective partnerships.
2. Research and development: Nigeria should allocate resources for R&D to advance PtX technologies tailored to Nigeria's energy needs. Partner with universities, research centres, and private companies to foster innovation.
3. Infrastructure development: There is a need to construct essential infrastructure for PtX systems, including renewable energy sources like solar and wind, facilities for producing hydrogen, and networks to transport and distribute hydrogen and PtX products.
4. PtX funding: To accelerate the adoption of PtX technologies in Nigeria, it is essential for the government to take proactive steps. One of the most effective strategies is to offer financial incentives, subsidies, and grants to entice private-sector investments in PtX projects. These incentives can take various forms, such as tax breaks, reduced import duties on PtX-related equipment, or direct cash grants for PtX initiatives. Furthermore, establishing a dedicated fund exclusively for PtX technology development and deployment is a prudent move. This fund can serve as a financial backbone for PtX projects, ensuring a stable source of capital to support research, pilot programs, and the scaling up of PtX infrastructure. By creating a favourable financial environment and dedicating resources to PtX initiatives, the Nigerian government can significantly boost private-sector involvement and investment in PtX technologies.

Abbreviations

PtX	Power to X
PtG	Power to gas
PtL	Power to liquid
NIPP	National integrated power project
NOAA	National oceanic and atmospheric administration
PHCN	Power holding company of Nigeria
GENCO	Generation company
VRE	Variable renewable energy
SEOC	Solid oxide electrolyzer
TWh/a	Terawatt hour per Anum
SMR	Steam methane reforming
CCS	Carbon capture and storage
CNG	Compressed natural gas
GHG	Greenhouse gas
GDP	Gross domestic product
ETP	Energy transition plan
IPP	Independent power producers
NEPA	National electric power authority
EPSR	Electric power sector reform
NIIMP	National integrated infrastructure manufacturers masterplan
PEM	Proton exchange Membrane
AGHA	Africa green hydrogen alliance
NiMet	Nigerian meteorological agency
CAGR	Compound annual growth rate
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
NERC	Nigerian electricity regulatory commission

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