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Exploring the role of green hydrogen for distributed energy access planning towards net-zero emissions in Nigeria

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Abstract

Providing sustainable, affordable, and reliable electricity through low-carbon energy development in the Nigerian energy sector is fundamental to ensuring energy security. Currently, efforts to harness the potential of renewable energy, to provide universal electricity access for all have not translated into significant economic development in Nigeria. Investment in green hydrogen could strengthen Nigeria's net-zero transition plan (NETP) and achieve sustainable energy access. The study explored the role of green hydrogen among five Electricity Distribution Companies (DisCos), from three geopolitical zones in Nigeria—North West, North Central, and North East. A bottom-up optimization linear programming methodology based on an open energy modelling framework (OEMOF) was used as the modelling paradigm. Secondary data mined from the Nigeria Energy Commission, Nigeria Electricity Regulatory Commission, NECAL 2050 report and international reports, and 2020 was used as a reference year to benchmark the model. The basic characteristics of the generation of electricity from green hydrogen, fuel cells, electrolyzers, and hydrogen storage, among other existing generation plants, were modelled till 2060 using modelled daily data obtained from Toktarova et al. (Electrical Power and Energy Systems 111:160–181, 2019). Outcomes from benchmarking led to two planning scenarios; these investigated possible insights that explored green hydrogen in Nigeria. Results showed that an integrated distributed approach would enhance harnessing green hydrogen in Nigeria, that is, electricity distribution among the DisCos. The study also revealed the following (1) the levelized cost of electricity could drop by about 8%, so also the cost of the investment; (2) access to electricity showed an improvement compared to the base year; and (3) emissions were cut in the power sector. To attain sustainable NETP with green hydrogen, the study recommends that a distributed generation approach among DisCos would support the national net-zero transition plan.

Keywords Green hydrogen, Nigeria power sector, Net zero, OEMOF, Renewable energy, Distributed generation, Net-zero transition plan, DisCos, Energy access

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Introduction

The role of the energy sector is significant in attaining countries' established climate targets because it is a sector that is found to be a focal point for abating anthropogenic emissions (IEA, 2020). Developing countries, especially sub-Saharan African (SSA) countries struggle to provide reliable and affordable modern energy to their growing population (Michoud & Hafner, 2021). In addition, countries in the region have fallen short of attaining their climate change commitments (Fawzy et al., 2020). These climate commitments are aimed at reducing risk and vulnerability to climate change, strengthening resilience, enhancing the well-being of people, and the capacity to anticipate and respond successfully to change (Eriksen et al., 2021).

In the SSA region, especially in Nigeria, energy poverty and meeting climate targets are intertwined, i.e. the country needs to tackle the twin challenges of energy poverty, which limits economic development, and climate change. Although several attempts, including the policy that aims at strengthening the renewable energy sector, have been legislated and implemented to combat these challenges, still, people of the region and country have yet to experience reasonably reliable and affordable modern energy services. This is evident in their very low per capita electricity consumption when compared to other developed regions in Europe and America.

To overcome the intermittent nature of renewable energy sources, storage devices are required. The expensive cost of electricity storage systems is a main setback to enabling the integration of renewable energy sources into the countries' energy mix. Due to the cost issue associated with storage facilities, the transformation of power to another form of fuel cells or gas (also, called power to *x*) has been gaining international attention. The use of fuel cells has largely found application in almost all sectors, including sectors that are difficult to decarbonize, i.e. transportation, heavy industries, and agriculture.

Hydrogen has a high energy content and is naturally available in nature in combination with oxygen gas. It is a significant source of fuel cells that could support the drive towards carbon neutrality through the electrolysis of water using electricity generated from renewable energy sources. Although a rigorous deployment of clean fuel cells has found application in several developed countries in Europe, and developed to support their energy transition strategies; most developing countries in SSA are yet to make frantic efforts to investigate how hydrogen and fuel cells could be utilized to holistically address the like challenges confronting the region.

This study employs the Open Energy Modelling Framework (OEMOF) to explore a system analysis and the role of green hydrogen technologies as a future energy carrier in the Nigerian power sector. This application supports low-carbon development and climate goals. It also considers the outlook and potential of green hydrogen as a future low-carbon fuel along with other technologies in the Nigerian energy mix. It explores how energy demand would be met across several suppressed demand scenarios through a distributed generation strategy. To do this the study utilized secondary data mined from national and international archives, the National Energy Master Plan, reports, Nigeria's demand profile extracted from global load projection presented in Toktarova et al., (2019), and insight from the analysis of stakeholder perspectives on the Nigerian energy evolution in Shari et al., (2023).

Background and green hydrogen technology

In recent years, many countries including Nigeria, have committed to net-zero emissions in their energy sector. It is expected that a globally ambitious net-zero emissions target capable of keeping global temperature increases to within 1.5 °C (IPCC, 2018), be set. This ambitious climate goal means striking a balance between GHG emitted to the atmosphere and the GHG removed from the atmosphere. Emissions from all energy end-uses must thus be reduced to reach this target. While energy efficiency, electrification, and renewables can achieve about 70% of the global mitigation needed as an orderly transition in the energy sector, hydrogen will be needed to decarbonize end-uses where other options are less mature or more costly (IRENA, 2022). Considering these applications, hydrogen could contribute about 10% of the mitigation needed to keep the global temperature increase to within 1.5 °C (IEA, 2021).

Hydrogen is not an energy source but an energy carrier (vector), which can be produced from multiple feedstocks, such as fossil fuels and renewable energy sources via electrolysis (shown in Fig. 1). Apart from electrolysis (involving splitting of water molecules), there are other methods of producing green hydrogen including decomposition of natural gas, solar hydrogen production, biological hydrogen production, and thermochemical splitting.[1] However, the aforementioned methods of producing green hydrogen have yet to be commercialized. Currently, hydrogen is produced on a commercial scale from fossil fuel sources and can be used across virtually any application at an industry scale such as in the steel and chemical industry and refinery, transport, heating, and power generation (Gielen et al., 2020).

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[1] https://www.futurebridge.com/industry/perspectives-energy/green-hydrogen-generation-overview-of-upcoming-technologies/.

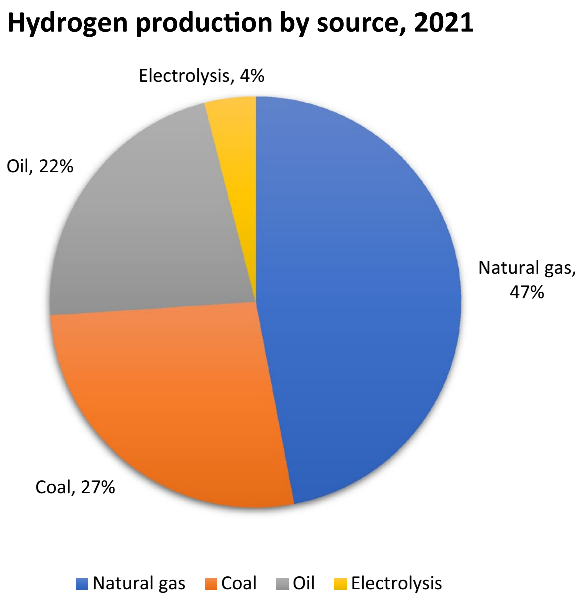

Fig. 1 Hydrogen production by source in 2021 (data source: IRENA, 2022)

Figure 1 shows that electrolytic hydrogen represents a meagre share of global electricity generation by source. This suggests that hydrogen production from renewable energy sources is largely experimental. In 2021, electricity generated from renewable energy accounted for about 33% of global electricity generation; this reflects that only about 1% of hydrogen output is produced from renewable energy. The implication is that electrolytic hydrogen remained limited, at about 700 MW in 2021 (IRENA, 2022).

According to BloombergNEF, grey hydrogen, or hydrogen produced with natural gas without abatement, and blue hydrogen produced with fossil fuel but subject to carbon capture in 2023 have an average production cost of around 2.13 and 3.10 US dollars per kilogram, respectively. Conversely, green hydrogen, which is produced from water electrolysis using renewable electricity has an average cost of about 6.40 US dollars per kilogram in 2023. It implies that green hydrogen is more expensive than its grey or blue counterpart (Schelling, 2023). In contrast, research by BloombergNEF revealed that by 2030 green hydrogen will be cheaper than grey hydrogen in some markets (Schelling, 2023).

Hydrogen production from renewable sources (green hydrogen or electrolytic hydrogen) is considered a potential source of a sustainable future and may unlock the global renewable energy trade. It is worth noting that electrolytic hydrogen can also enhance sustainable CO_2 capture when CO_2 reacts with hydrogen, which in turn forms synthetic fuel and acts as a reducing agent to replace coal in iron production (IRENA, 2022). Also, nitrogen being a main component of greenhouse gases when reacted with green hydrogen produces green ammonia which can be used as feedstock for green fertilizers. This means that the hydrogen needed to make ammonia will come from water using electrolysis based on renewable electricity (Ramachandran & Menon, 1998). The hydrogen derivatives produced, further enhance the energy density of hydrogen, making long-distance transport and long-term storage cost-effective (Di Lullo et al., 2022; HFW, 2022). For instance, liquid ammonia a derivative of hydrogen is about eight times the energy density (MJ/m^3) of lithium-ion batteries. The high energy density of the hydrogen derivative implies that hydrogen energy can be transported cost-effectively (IRENA, 2022).

The adoption of several hydrogen derivatives would reduce global dependency on fossil fuel resources. This would likely enable the timely attainment of national/global energy transition targets. The global energy trade through hydrogen derivatives would provide economic benefits as importing countries can tap into cheaper (than domestic) resources, thereby improving the resilience of the system since there would be alternative ways to satisfy final energy demand, hence strengthening energy security. Also, the development of green hydrogen and associated derivatives is significant in enhancing a circular economy and creating green jobs while meeting international and national energy demand (Kabir et al., 2023; Štuller et al., 2022). Further, most developing countries are heavily dependent on fossil fuels despite having high renewable potential. On this note, Panchenko et al. (2023) claimed that investment in hydrogen derivatives could tackle energy insecurity, accelerate green electricity production, and improve renewable energy resources exploitation.

About the present and foreseeable energy future, hydrogen could have several attributes and benefits on a global and national scale. It is therefore imperative that the developed and developing countries embrace hydrogen as a future fuel and position themselves at the technological frontier. This will assist the countries in their drive towards carbon neutrality. These opportunities are in power generation, heat for industry, transportation, storage, and low-carbon hydrogen (IRENA, 2023). The abundance of renewable energy resources in sub-Saharan Africa implies that countries in the West African corridor can harness the potential of hydrogen fuel cells to light up homes and businesses, and also support the global climate neutrality agenda (Baye et al., 2021).

Solar potential is abundant in Nigeria, estimated at over 427 GW where an average of 6,372,613 PJ/year of solar energy is received across the entire country (Ohunakin, 2010; Newsom, 2012). In addition, water resources comprising surface water of about 267 billion cubic meters and enormous groundwater resources estimated at 52 billion cubic meters of replenishable yield per year, exist in basement complex that covers over 60% of Nigeria (Oteze, 1981; Maduabuchi, 2004; Newsom, 2012; USAID, 2021). These and many more are among the numerous energy resources found in Nigeria. The availability of these enormous renewable resources indicates that the country can provide natural feedstocks for electrolytic hydrogen fuel cells. This is an opportunity for Nigeria to generate alternative energy to cater for the demand of the growing population by complementing the existing technologies to attain energy sufficiency and economic growth.

While hydrogen alone cannot halt climate change, its high energy content per unit weight compared to gasoline or diesel is an excellent clean future fuel cell in the energy mix that could help ameliorate climate impacts. It is an effective alternative energy fuel in the power sector, heavy industries, and transport sector; hence, it tends to drive the low-carbon agenda in the net-zero transition plan. There is thus the need for the country to position itself at the technology frontier to take full advantage of the energy transition opportunities. These opportunities are in the production, transportation, storage, and use of renewable hydrogen.

Green hydrogen value chain

This sub-section discusses the challenges that are associated with the use of green hydrogen in the context of decentralized systems. The main challenges that exist in the green hydrogen value chain, include hydrogen production, storage and transportation. Also, some applications of the levelized cost of green hydrogen in a decentralized system will be discussed. Qureshi et al. (2023) explicitly conducted a state-of-the-art review of hydrogen (H_2) production, storage, transportation techniques and its challenges based on its techno-economic feasibility. Several production techniques were identified, including steam reforming, Plasma reforming, partial oxidation, water electrolysis, photoelectrolysis and pyrolysis.

However, recent trends to explore the systematic production of hydrogen using renewable energy sources (called green/renewable hydrogen) have emerged as the most efficient H_2 extraction processes. Renewable H_2 production is efficient because it uses water and only produces pure oxygen as a by-product through the water electrolysis process. Also, this process is crucial to supporting the transition to a low-carbon economy and developing a strategic net-zero emission planning for both developed and developing countries. The electrolysis processes often use direct current power from clean energy sources such as sun, wind, and biomass. In the production process, electrolyzers play a pivotal role by employing green electricity to dissociate water molecules into H_2 and oxygen in the production of green hydrogen. However, the amount of green hydrogen produced through this process is about 4% contributing to a significant economic constraint. Among many significant obstacles that prevent the widespread use of renewable H_2, include its high production cost.

For renewable H_2 to serve its transition purposes, its storage and transportation are crucial aspects of achieving the reality of renewable hydrogen towards net-zero emissions planning. The significantly low energy density has made storing green hydrogen challenging, especially when transporting or used as fuel tanks. Such fuel tanks will have to be big enough with a high volumetric, gravimetric storage unit, low cost, lightweight, excellent adsorption, desorption kinetics and recyclability. As a result, H_2 storage systems can be either physical-based or material-based. While hydrogen can be physically stored as a liquid at cryogenic temperatures due to its low boiling point or as a gas at high-pressure tanks, hydrogen storage materials such as hollow spheres, carbon-based materials, zeolites, and metal–organic frameworks are potential materials to store H_2 (Yang et al., 2023; Le et al., 2024).

Hydrogen can be transported from the production site and distributed to the end consumer by road, pipeline and shipping, however, the transportation mode depends on the hydrogen volumes, delivery distances and other local conditions. Road transportation mode is ideal for conveying small hydrogen demand across up to 100 km in pressured vessels, and large amounts of gaseous hydrogen can be transported through pipelines to meet large demands for hydrogen at about 500 km and it is the most economical way to transport hydrogen (Yang et al., 2023). The existing natural gas pipeline can be modified and adapted to transport gaseous hydrogen this is likely to reduce investment in transporting large gaseous hydrogen. Although hydrogen transportation through pipelines is considered a viable option for long-distance transport, it is geographically constrained. In a global context, transporting hydrogen over the sea is the most economical option, as it enables hydrogen trade between countries for long-distance transport of over 1000 km.

The levelized cost of green hydrogen and electrolyzers

The cost of hydrogen is a major determinant of its proliferation as an alternative fuel source for carbon neutrality and nations' net-zero emissions ambition. One of the major challenges in the short-to-medium term is that green hydrogen is still more expensive than blue hydrogen. According to the H2-Atlas.

The Levelized Cost of Green Hydrogen (LCGH) compared with the levelized cost of other forms of hydrogen and fossil fuels sources is a function of the economics based on the electrolysis technologies employed such as alkaline electrolysis (AE) and proton exchange membrane (PEM), with green electricity sources (Man et al., 2024) and high-temperature (HT) electrolysis. However, green electricity sources from solar energy will be the predominant energy for green hydrogen production in the future. AE exhibits a levelized cost of hydrogen (LCH) of about 3.18–8.74 USD/kg which is more competitive than the PEM with an LCOH of around 3.33–10.24 USD/kg for hydrogen production (Man et al., 2024).

Also, for in situ green hydrogen production studies from de la Cruz-Soto et al., (2024), revealed that due to income generated from energy exportation a grid-interconnected Power-to-Gas (P2G) system can have a reduced LCOH when compared to decentralized green hydrogen. It could be inferred that green hydrogen from solar PV sources combined with the alkaline electrolysis in large-scale green hydrogen production could achieve a low LCGH, especially in developing countries, while a PEM is suggested to be cost-effective in cases with high power fluctuation and end-devices, which is the case in many sub-Saharan African countries (Man et al., 2024).

However, the utilization and market viability of HT electrolysis have not matured enough to gain significant market value (Yadav & Banerjee, 2020), although with higher efficiency compared to other electrolysis processes (Wendt et al., 2022). However, the efficiency of most electrolyzers is about 67%, in simple terms it implies that it takes around 50kWh of electrical energy to electrolytically produce 1 kg of hydrogen which has an energy content of around 33.33 kWh. It then means that about 1.5 units of energy are to produce one unit of hydrogen (Roeb et al., 2020). It implies that the low-efficiency rate and prohibitive cost of green hydrogen have significantly weakened the enforcement of green hydrogen vehicles in many developing nations, including Nigeria, thus making it a relatively immature technology in the region (Abou-Seada & Hatem, 2022).

Understanding the cost of hydrogen from several producing sources is considered thus: producing hydrogen from natural gas costs between €0.03/kWh of H_2 and €0.06/kWh of H_2. Conversely, producing green hydrogen by electrolysis costs between €0.10/kWh of H_2 and €0.15/kWh of H_2. However, the cost of producing green hydrogen is expected to decrease in the future owing to the reduced cost of electricity from solar and wind energy (Prognos, 2020). The Hydrogen Council estimates that costs between €0.017/kWh H_2 and €0.05/kWh H_2 will be achievable by 2050 (Hydrogen Council, 2020); whereas, the levelized cost of green hydrogen is between $4/kg and $17.4/kg in Nigeria, compared with between $2.8 and $3.5 per kg for blue hydrogen. It, therefore, appears to be uncompetitive to deploy green hydrogen at the moment, which may be the reason why the Nigerian Energy Transition Plan sees it playing a role only after 2030 (Ebii, 2023).

In addition, green hydrogen production costs are usually largely determined by the electricity supply costs (renewable energy sources), the investment costs such as capital expenditure (CAPEX) of the electrolysis system and its utilization (annual full load hours) (H2 Diplo, 2024). Also, the hydrogen production costs such as the techno-economic parameters of the electrolyzer or the CAPEX of the PV and wind power plants are determined via the world market and differ marginally between regions. For instance, in a green hydrogen plant the solar photovoltaic, wind turbines and hydrogen electrolysis have 1,470,000 €/MW, 1,580,000 €/MW and 1,250,000 €/MW CAPEX, respectively (Halloran et al., 2024). Electricity from wind energy is still costly compare to other production sources.

The Nigerian energy sector

Several challenges confronting Nigeria's power sector, including unavailability of gas, machine breakdowns, seasonal water shortages, and limited grid capacity, have severely limited the operational performance of power generator plants (Roche et al., 2020). This situation has led to acute shortages of electricity supply across the country with blackouts lasting for several hours in a day. Despite challenges confronting the energy sector, Nigeria is committed to achieving net-zero by 2060. The plan presents an opportunity for Nigeria to generate alternative energy to cater for its growing population and attain energy sufficiency and economic growth. In addition, it will also create legitimate well-paying green jobs (ETP, 2022).

In August 2022, Nigeria officially launched its net-zero energy transition plan (ETP) aimed at changing energy production and use, with increased removal of greenhouse gases from the atmosphere while improving electricity access. It also includes plans to integrate green hydrogen into her energy mix as a potential future clean fuel cell. The outlined strategies include but are not limited to (i) generating electricity without emissions; (ii) using electric vehicles; (iii) deploying carbon capture and storage, and direct air capture; and (iv) utilizing hydrogen as an alternative fuel, among others (ETP, 2022).

Although the government has presented a clear pathway to meet demand across the centralized and decentralized power area, it has not explored in detail the role of green hydrogen as a future energy carrier in the net-zero emissions target. Against this backdrop, the study in this chapter aims to explore the prospects and dynamics of green hydrogen in the Nigerian energy transition plan. It also assesses different decentralization strategies that meet suppressed demand. Hence, to examine hydrogen utilization and decentralization strategies in the Nigerian power sector, the following research questions are considered:

i. How will suppressed demand be met in an energy mix with different net-zero emissions targets, and different energy mixes including renewable energy, hydrogen fuel cells, and nuclear energy?
ii. What energy mix would be deployed to fully decentralize pathways for the Nigerian power sector?

To achieve this, the study explores a distributed assessment of green hydrogen production among five electricity Distribution Companies (DisCos), from three geopolitical zones in Nigeria including North West, North Central, and North East. In addition, scenarios that consider fuel switching, energy efficiency, nuclear, and investment in renewable energy (both on-grid and off-grid) are considered. This implies that a dual modelling approach would be applied based on (i) a system thinking approach from a stakeholder's perspective analysis by Shari et al., (2023), and (ii) a bottom-up optimization linear programming methodology based on an open energy modelling framework (OEMOF), was used as the modelling paradigm.

The role of hydrogen in the Nigerian power sector

In the past, hydrogen was only considered a fuel cell for transport, heat, and industries. In recent years, developed and developing countries have embraced hydrogen fuel cells as a major part of their net-zero emissions strategy. Hydrogen end-use technology and its application demonstrate that the hydrogen economy is crucial to achieving net-zero emissions targets both in developed and developing countries (van der Spek et al., 2022). The high energy density of hydrogen (earlier discussed), has made it a significant source of energy in major heat-dependent sectors.

The investment in hydrogen globally as a future low-carbon fuel is not farfetched. These efforts could be attributed to some of the following benefits (i) compatibility with conventional diesel or gasoline trucks; (ii) hydrogen energy density (hydrogen has an energy density of about 120 MJ/kg when compared to diesel having energy density of 45.5 MJ/kg and gasoline with 45.8 MJ/kg; in terms of electrical power, this implies that the energy density of a hydrogen fuel cell is equivalent to 33.6 kWh of usable energy per 1 kg, compared to diesel or gasoline which is about 12–13 kWh per kg (Molloy, 2019)); (iii) high efficiency (50% of the energy generated by an internal combustion engine is converted to heat, while electric drive train powered by hydrogen only loses about 10% to heat); (iv) hydrogen stands better chances in price reduction of more than 50% lower than diesel in the next decade; the price of fossil fuels is unstable and might not decline coupled with the Russia–Ukraine issues. Considering all these factors and more, there are better chances for hydrogen to gain the attention of world leaders as a main energy vector to achieve their carbon neutrality ambitions, as it is an efficient, cheaper and economically sustainable future energy carrier.

It is worth noting that electricity from hydrogen comes with its limitations: (i) hydrogen gas is colourless, odourless, and highly flammable; hence, detecting leakages could occur unnoticed and could be disastrous; (ii) the pathways to the production of green hydrogen or renewable hydrogen is unclear; (iii) there are still unclear pathways to which the technology of producing renewable could be scaled in the future as the technology is yet to be fully exploited on a larger scale; (iv) costly storage poses a major limitation. Hydrogen is produced in gaseous form and needs to be pressurized or liquefied thus requiring more energy. However, there are emerging methods that use chemical bonds called liquid organic hydrogen carriers (LOHC) or ammonia to transport hydrogen in a stable state. These methods do not require pressure or cryogenic liquefaction and thus utilize less energy to transport and store hydrogen, although the technology is still in the pilot stage (Molloy, 2019).

Although the use of hydrogen as feedstock in industries has been well-established for over six decades (Fan et al., 2021), green hydrogen is currently widely researched as a fuel cell for cars, production of fertilizers, and electricity; it has recently emerged as a potential solution to decarbonize heavy transport because it releases almost three times the energy of what can be obtained from gasoline/petrol or diesel (Molloy, 2019). From a broader perspective, the world is making frantic efforts to produce, utilize, and commercialize electrolytic green hydrogen due to the benefits it offers for decarbonizing the industrial, chemical, and transportation sectors.[2] The European Union (EU) identifies the role of green hydrogen in achieving its climate targets and helping reduce CO_2 output from sectors difficult to decarbonize; in this light, the European Green Deal (EGD) recognizes hydrogen as key

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[2] https://www.weforum.org/agenda/2021/06/4-technologies-accelerating-green-hydrogen-revolution/.

to a clean and circular economy.[3] It is indeed pertinent to know that plans to invest in hydrogen fuel cells have recently gained momentum in SSA countries, as countries are reviewing their energy acts to include renewable energy sources and green hydrogen in their energy mixes (IEA, 2022; Kobina & Stephanie, 2022). For example, in 2021, Namibia announced an estimated 9.4 billion USD green hydrogen project by 2026.[4]

Further, it is evident that investment in green hydrogen is veritable, several EU countries have signed a treaty with some West African countries to trade hydrogen fuel cells. The treaty to develop green hydrogen is unprecedented and has the potential to open up the green hydrogen fuel cell market of the ECOWAS region in the future. For instance, the German Ministry of Education signed a treaty with Niger to generate and export green hydrogen in the region (Bhandari, 2022). Meanwhile, countries like Kenya, Nigeria, and Morocco are at various stages of developing plans to integrate green hydrogen into their energy mix for the mid- and long-term. Also, at COP26 in Glasgow, the United Nations pledged to support South Africa's Just Energy Transition with about 8.5 billion USD to develop upcoming economic opportunities in green hydrogen, and a 17.8 billion USD plan to support a pipeline of green hydrogen (Yohannes & Diedou, 2022).

The report of the International Renewable Energy Agency (IRENA) report on the Nigeria Renewable Energy Road Map revealed that the potential of renewable energy will not only help to meet Nigeria's large energy deficits, but also power sustainable economic growth and create jobs while achieving global climate and sustainable development objectives (IRENA, 2023). With the renewable energy potential, green hydrogen would be emerging as a frontrunner for achieving a clean, secure, just, and affordable energy future for Nigeria and the entire Africa; this will greatly support economic opportunities for Nigeria's economy (Africa's Green Hydrogen Potential, 2022). With the abundant wind and solar potentials, many parts of Nigeria are ideally positioned for green hydrogen production to build their energy dependence and industrialization, while also meeting rising national energy demand.

Further, an advisory report prepared by the Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ) Gmbh claimed that large renewable energy systems for commercial and industrial (C&I) purposes, that utilize solar PV solutions in an off-grid solar hybrid mini-grid rely heavily on diesel generator sets for backup power (Gorre & Nweke-Eze, 2023). However, recent research revealed that the country such application of renewable energy can be achieved complementarily using electrolyzers and fuel cells in a decentralized framework and achieving net-zero emissions objectives, such as energy access, producing green hydrogen and displacing petrol and diesel generator sets.

In 2022, Nigeria launched its roadmap to carbon neutrality by 2060, and an estimated sum of 1.9 Trillion USD is required (ETP, 2022). As part of the decarbonization strategy of the country's net-zero targets, Nigeria has made plans to include about 9 GW and 34 GW of renewable energies by 2040 and 2050, respectively, in its power mix, in addition to a 4 GW and 22 GW capacity for hydrogen electrolyzer storage by 2040 and 2050. Electricity demand of about 1 TWh and 46 TWh is projected to be met by electricity generated from electrolytic hydrogen in 2040 and 2050, respectively (ETP, 2022).

Green hydrogen in Nigeria's decentralized energy sector

Currently, about 80% of Nigeria's operational energy capacity comes from off-grid diesel/petrol generators. Access to electricity is further made difficult due to the constant increase in the price of diesel fuel as well as the expensive acquisition and maintenance costs of diesel generators. The poor energy situation in Nigeria is exacerbated by the current increase in the grid electricity by about 240% making more people rely on diesel/petrol generators. However, measures to promote power generation in Nigeria are focused on mini-grids and solar home systems (SHS) based on renewable energy sources such as photovoltaic, bioenergy and hydroelectric power.

Nigeria like other countries in the tropics possesses exceptional solar resources that have enormous potential for producing green hydrogen. The potential contribution of green hydrogen to the Nigerian energy sector includes but is not limited to the following: (i) contribution towards energy transition and advancing net-zero emissions plan; (ii) contribution to energy access; and (iii) stabilization of renewable energy system grid-connected. However, the choice to invest in green hydrogen is largely dependent on the cost, also other factors include policy and regulation, infrastructure, logistics, local demand, and export trade.

Although there are a few private decentralized hydrogen projects in Nigeria, more are underway. To develop decentralized hydrogen projects in Nigeria there is a need for Nigeria to develop a clear and comprehensive technical and economic feasibility study. Assessing the technical and economic feasibility of green hydrogen projects for decentralized energy applications and supporting decarbonization efforts requires a comprehensive evaluation of various factors which include:

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[3] https://www.intereconomics.eu/contents/year/2021/number/6/article/green-hydrogen-in-europe-do-strategies-meet-expectations.html.

[4] https://fuelcellsworks.com/news/namibia-announces-9-4-billion-green-hydrogen-project/.

A. Resource availability: Resources such as solar, wind, hydropower and biomass are essential for generating green/renewable hydrogen to support decentralization and decarbonization efforts. Nigeria has a high potential for renewable energy resources well distributed across different parts of the country, such as solar, biomass and hydropower resources in the northern, and southern parts of the country. Also, wind energy is in the core northern region and along the coastal area.
B. Electrolyze and fuel cell technologies: Electrolyzers are the spinal for producing green hydrogen. Although the efficiency of many electrolyzers is around 67%. There are pieces of evidence that the efficiency and cost will be competitive in the future. This implies that with a competitive cost and high efficiency of electrolyzers Nigeria can leverage to provide energy security while supporting the country's decarbonization efforts.
C. Infrastructure development: Currently, Nigeria's energy infrastructure is not mature and resilient enough to support renewable energy integration, let alone green hydrogen. However, future decarbonization efforts should consider green hydrogen production storage and distribution in a decentralized application model. This would include pipelines, storage facilities, transportation means, and refuelling stations.
D. Demand and market analysis: An effective distributed energy generation effort would require a thorough analysis of the potential demand for electricity in decentralized settings for a targeted market. Other evaluations and assessment analyses include evaluating the market size, growth potential, and competition, regulatory support for hydrogen adoption in decentralized systems
E. Project financing and funding: There is a need to evaluate the financial viability of the project, considering upfront investment costs, potential revenue streams, and payback periods. Such efforts would facilitate investors to consider investing in the green hydrogen market in Nigeria and thus would enhance collaboration and partnerships
F. Risk assessment and life-cycle assessment: Scaling up hydrogen would require a life-cycle emissions assessment as hydrogen is one of the keys to energy transitions. It is therefore not only important to make it economically viable, but also to maximize its decarbonization potential and minimize its impact on resources, such as water. For instance, hydrogen from natural gas with a 98% CCS capture rate using ATR technology will achieve life-cycle emissions comparable to 100% solar powered electrolysis when the ATR is powered with fully decarbonized energy. This implies that a risk and life-cycle assessment could enable the full scaling up of green hydrogen production and end users in a decentralized energy system.

Methodology

This section presents the methodology to explore a low-carbon strategy for a typical developing country that explores carbon neutrality in a set timeframe. An open-source energy modelling tool is applied to the Nigerian energy system with a focus on the role of renewable energy towards a transition to net-zero emissions targets, and developing a carbon–neutral strategy. In this case, the open energy modelling framework (OEMOF) is employed to investigate the role of green hydrogen as a future energy carrier in the Nigerian power sector toward its net-zero energy transition plan under different electrification pathways and policy constraints. This optimization modelling approach synthesizes and reflects in-depth insights not only on how the electric energy demand of (i) existing, (ii) suppressed, and (iii) non-electrified people can be met, but also explores the strategic role of renewable hydrogen in Nigeria's net-zero emissions target. To do this, six scenarios were defined based on the government's intended energy transition plans (Current Policy Scenarios), and net-zero emission scenarios with energy efficiency (Best Policy Scenarios); also, the role of green hydrogen in distributed electricity generation among the electricity Distribution Companies (DisCOs) in Nigeria is investigated. The scenarios were designed based on the power sector—Nigeria Energy Transition Plan (ETP). Also, the scenario was based on the assumption that the Distribution Companies would serve as a standard to enhance a distributed and decentralized hydrogen strategy in the country.

The OEMOF framework and its building block

Oemof is an energy system modelling platform database integrated with Python (pandas) libraries, based on a modular open-source framework (Oemof-Team, 2020). Through collaborative development in an academic context based on open processes, oemof was developed to support a maximum level of participation, transparency, and open science principles in energy systems modelling (Hilpert et al., 2018). Hence, enhancing a prominent level of scientific standards (transparency, repeatability, reproducibility, and scrutiny) became pertinent to the overall system's model framework. The oemof framework is based on a generic graph-based description of energy systems (Oemof-Team, 2020). It is differentiated into several dichotomies of energy system models that each is specified for a certain task in the energy system modelling process, of which, oemof-solph is one of its significant parts (Hilpert et al., 2017a).

Oemof-solph or solph is part of oemof (a meta-package), which has been developed to serve as an integrated energy system model (Krien et al., 2020b). It generates energy system simulation and optimization models which are designed to solve linear problems (LP) or mixed-integer linear optimization problems (MILP) from a generic object-oriented structure based on graph theory (Krien et al., 2020a). Oemof-solph is built on the Python optimization model language (pyomo). Pyomo is an open-source modelling tool that provides classes and functions designed to create optimization functions via an Application Programming Interface (API) (Hart et al., 2019). It enhances its functionalities to simulate or optimize multi-regional energy systems considering power, heat, and mobility. Its structure enables us to generate models on various levels of detail by employing predefined components and other possible additional expressions and formulation constraints; also, it is possible to switch between a dispatch and an investment model (Hilpert et al., 2017b).

Oemof-solph employs a modular and generic system approach.[5] Oemof includes components such as energy technology transformation. Other major constituents include (i) generation systems such as cogeneration, natural gas plants, solar arrays, wind turbines, diesel generators, etc.; (ii) transporting energy which consists of an electricity grid network; (iii) electricity consumer/demand types viz. residential, commercial, and industrial consumers; (iv) fuel such as gas and oil or hydrogen; and (v) export in which excess electricity generation is distributed where possible.

To simplify the rigorous modelling efforts in oemof, oemof-B3 was introduced which was used as a sector integrated energy system model of Brandenburg and Berlin, Germany. It represents many sectors including electricity, centralized and decentralized heat, hydrogen, CO_2, and methane. It is a multi-node model, which means that several distinct regions are represented that are connected via transmission lines (Oemof-B3, 2023). The model is a perfect foresight, cost-minimizing linear optimization model based on oemof-solph, oemof Tabular and oemoflex. The oemof-B3 has been adopted to develop a regional integrated model that explores how power systems are modelled in a distributed-generated approach.

Graph theory also known as the bipartite graph is a mathematical study of graphs. They are mathematical structure models with pairwise relationships between objects. An oemof graph is represented as a network of nodes and edges. A node can either be a bus or a component; the bus is a virtual element that connects different components of the energy system and must be balanced at every stage of the system. Also, a bus corresponds to a node or cell in the energy system. The edges represent the input and output of a component, they consist of flows, the flow is a very significant component of oemof because the edge is responsible for energy flow between two nodes and is often used to measure system costs. Figure 2a shows a diagrammatic illustration of graph theory, comprising nodes, edges, bus, component, and flow. Figure 2b shows the basic representative use and flow of the oemof model.

The generic approach to modelling in Oemof is divided into two levels viz. components and graphs. The components consist of a source, sink, and transformer. The source is explained as having one output with no input. It can be used to model energy sources such as solar and wind power plants, coal, gas and oil power plants. On the other hand, the sink has one input, no output, which is employed to model energy consumers, energy excess, or a reduction in energy consumption, while the transformer connects inflows to outflows through one or more conversion factors. In this regard, it can be used to simulate power plants such as Combined Heat and Power (CHP) Plants, or gas turbines that operate with a constant efficiency or capacity factor.

Figure 2a shows a graphic theory as it is applied to an oemof framework and its virtual representation in Fig. 2b. Figure 3 presents a schematic illustration of a simplified energy system in an oemof framework. Figure 3 further demonstrates how the oemof model framework can be employed to model a simplified energy system. Renewable and fossil fuel energy represents the energy source, the storage system represented here is a general storage scheme as it has not distinguished between different types of storage systems. As seen in Fig. 3, the storage allows a dual energy flow, i.e. electricity/current stored could be released when needed. Also, Fig. 3 illustrates two types of sinks, the demand or energy consumers and excess energy that could be exported to other consumers.

Transformers are represented as inverters, rectifiers, and fuel generator sets. This implies that energy sources such as solar or fossil sources could be transformed into useful energy. Examples of such transformers found in fuel generators are conventional diesel/petrol generator sets, and gas or oil power plants. The inverter converts direct current (DC) generated from renewable energy like solar panels to alternative current (AC) found compatible with consumer appliances. Conversely, alternative electrical currents generated from non-renewable sources

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[5] https://oemof-solph.readthedocs.io/en/latest/reference/oemof.solph.components.html.

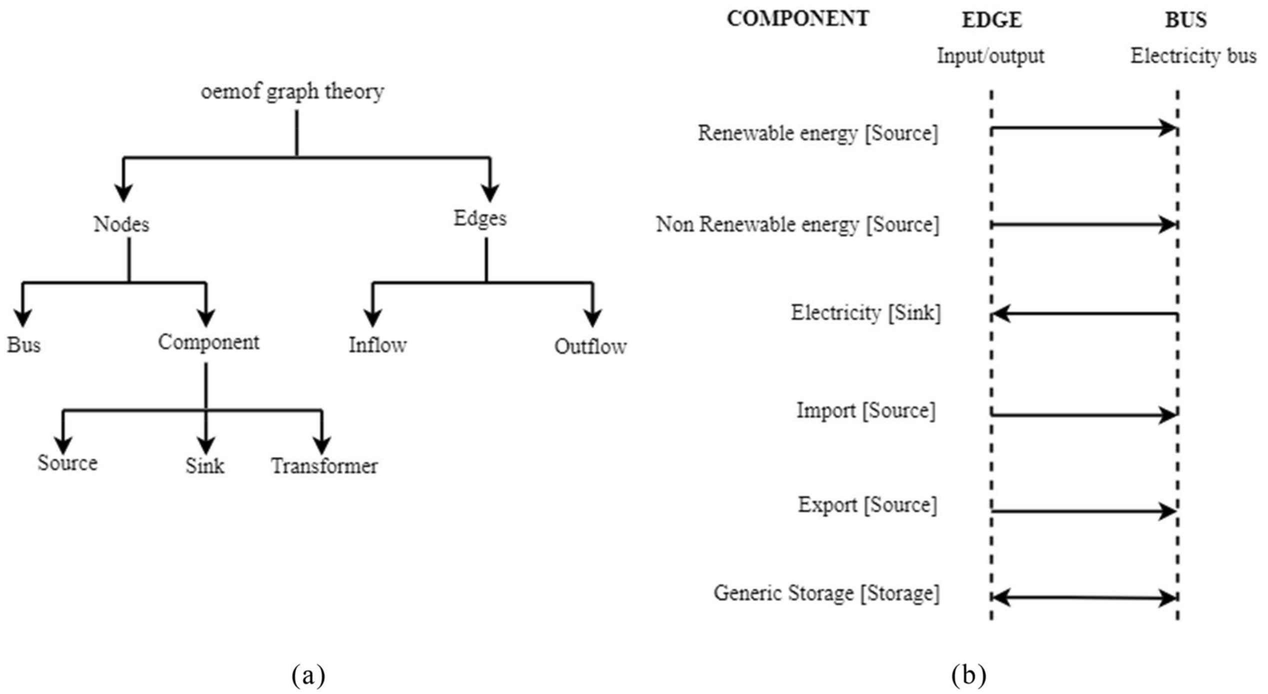

Fig. 2 **a** Illustration of the graph theory, and **b** basic representative flow of the oemof model

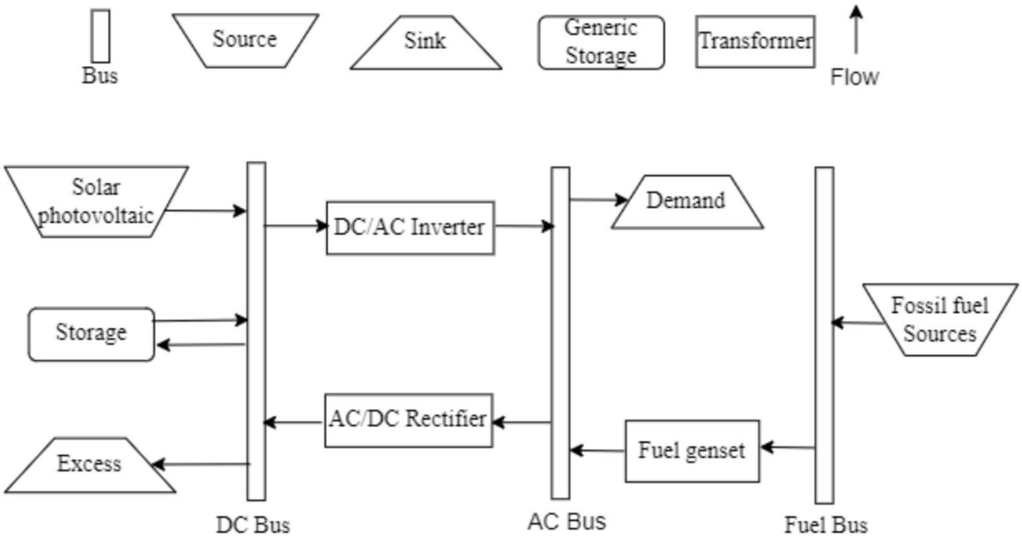

Fig. 3 Schematic illustration of a simplified energy system in oemof

(through power plants) are converted into a direct current by using a rectifier. This electricity converted from AC to DC is to enable the current to be saved in batteries/storage devices for later usage.

System analysis of green hydrogen technology

The oemof-solph framework is adopted to explore the system analysis of green hydrogen technology in the Nigerian power sector, towards the carbon neutrality target. Figure 4 shows the reference energy system (RES) by which the oemof framework would adopt to model Nigeria's power sector through coupling hydrogen technology.

According to Fig. 4, the far left represents primary energy sources which include gas, fuel oil, diesel, nuclear, biomass, wood fuel and geothermal. The energy sources are processed into useful energy, i.e. electricity, by

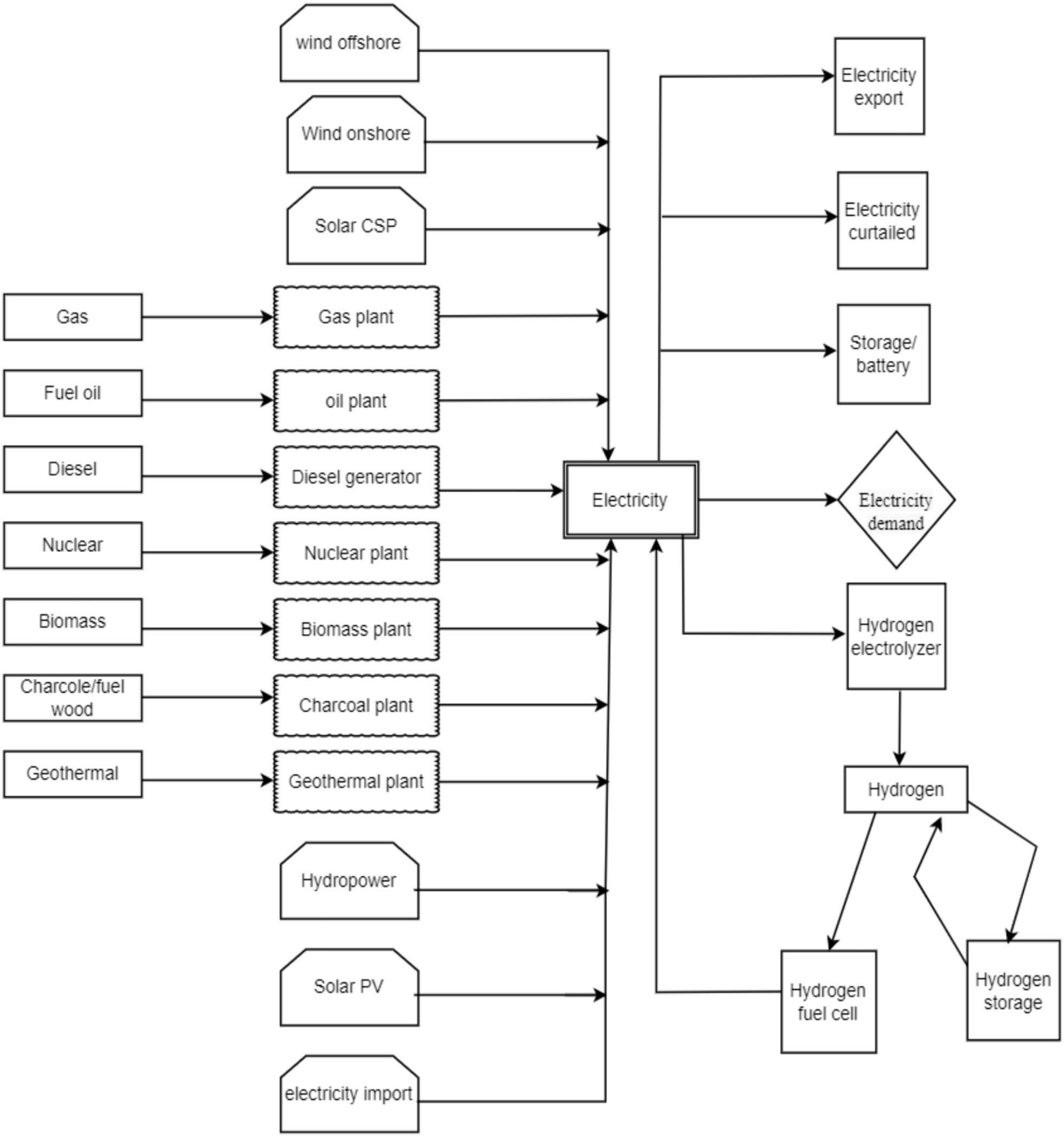

Fig. 4 The reference energy framework for the power sector coupling

the various power plants; however, renewable energy sources are also sources of electricity including electricity imports. To the far right suggest several uses and applications of electricity generated, which include electricity export, curtailment, storage and electrolyzer. The purpose of the RES is for the electricity demand to be met with consideration to power-to-gas (P2G) or a sector coupling arrangement, thus forming a key power sector coupling.

The right side of Fig. 4 represents the process of exporting, curtailing or storing excess electricity for later usage. Also, excess electrical energy is converted into storable chemical energy in batteries. More so, the excess electricity generated is used in a hydrogen electrolyzer which

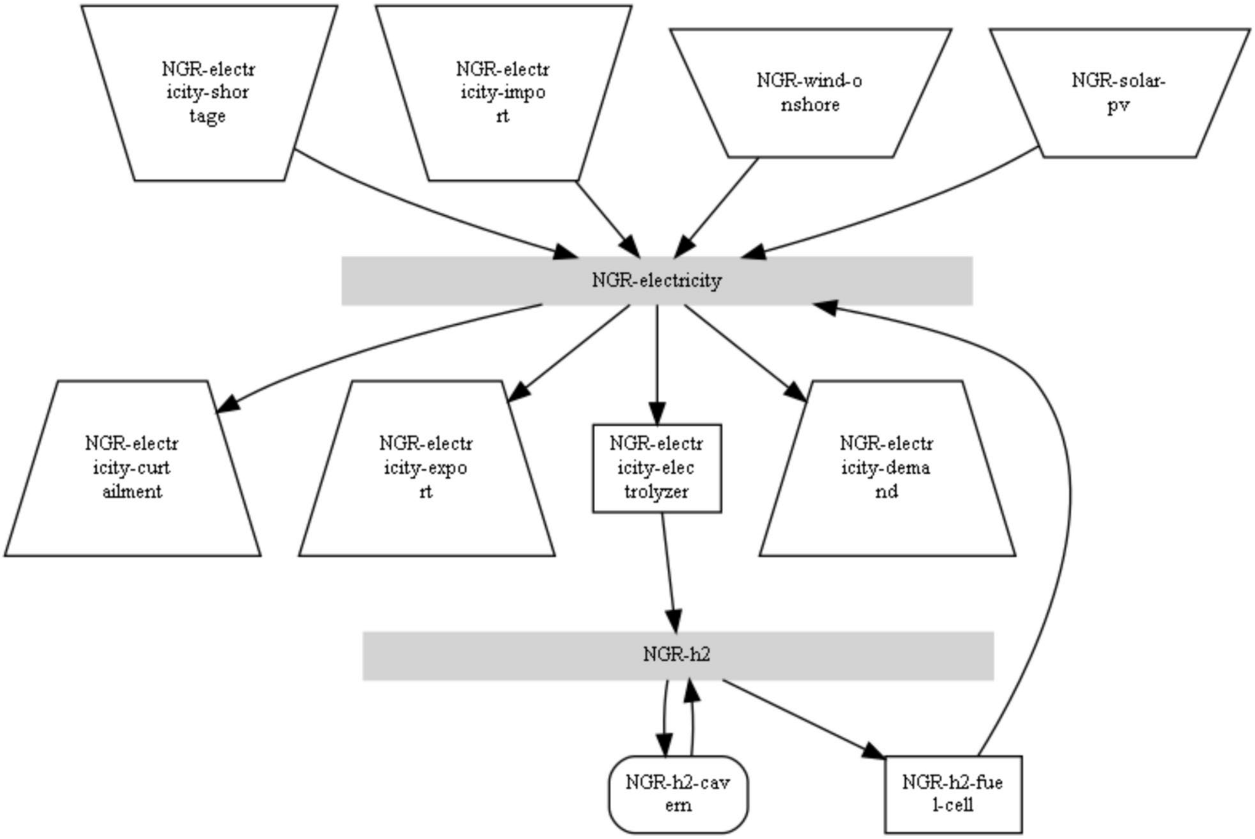

Fig. 5 A simplified oemof model output for green hydrogen

involves the use of electricity to separate water into hydrogen and oxygen gas (although the process of electrolysis of water is more advanced than what is presented in Fig. 4). The oxygen gas produced is released into the atmosphere, while the resulting hydrogen gas is stored and used when required, or made to be recombined with oxygen gas in a fuel cell. To make the hydrogen gas produced from the electrolyzer useful, the fuel cell is used. The hydrogen fuel cell then converts the hydrogen into electricity to meet electrical energy demand.

Figure 5 shows a clearer model of green hydrogen production in Nigeria. Here, the oemof conventional symbols have been used to represent how hydrogen can be generated from excess electricity obtained from renewable energy sources.

Model scenarios

Scenarios are developed to investigate the research questions. Table 1 describes scenarios that are aimed at meeting energy demand, suppressed demand, and non-electrified demand. The load curve for Nigeria used to estimate hourly electricity demand was retrieved from Toktarova et al., (2019), and modified to fit the scope of the scenarios. The outcome was then used as a benchmark to model the development scenarios that explore how to achieve net-zero emissions targets while meeting demand. It is important to reiterate that assumptions used for the scenarios are taken from the analysis of the stakeholders' perspectives in Shari et al., (2023).

Three scenarios are presented in Table 1, including the business as usual (BAU), the sustainable scenario, and the carbon-neutral scenario and are based on the ETP power sector. The BAU scenario describes the current energy situation and the current energy growth in Nigeria. It assumes the energy status quo across the 2030, 2040 and 2060 modelling periods. Each model period details the input assumptions. The 2030 model period assumes gradual investment in solar energy for off-grid according to the Rural Electrification Agency (REA) report (REA, 2016), while the 2045 and 2060 model period assumes that natural gas as a transition fuel with decreased captive diesel generators, and also with a significant investment in solar technology to provide for the reduction in diesel usage, respectively.

The sustainable scenario describes a rigorous investment in renewable energy targets both for off-grid and

Table 1 Scenario development and description of net-zero emissions target

Scenario	Description	Assumption
Business as usual (BAU)	This considers the current energy situation from 2020. Considers current status quo and energy growth rate in renewable energy (RE) on-grid/off-grid and prosumers for underserved areas	2030—gradual investment. in decentralization 2045—gas as a transition fuel with decreased captive diesel generators 2060—a significant investment in solar technology reduction in diesel and at an increased demand based on an 8% GDP growth rate
Sustainable	This considers rigorous investment in RE—on-grid/off-grid and prosumers and energy efficiency on the demand side, while reducing diesel gen use above BAU, improved gas. Model values adopted from the current NETP and NDC (NETP, 2022)	2030—RE grows by 30% and investment in EE according to NDC 2045—more investment in RE and EE according to conditional NDC 2060—Outlaw the use of diesel generators and an increased demand based on 11% GDP growth rate
Carbon neutral	To achieve net-zero investments in nuclear, bioenergy, hydrogen and fuel cells are considered beyond the sustainable scenario	2030—net-zero plan 2045—gradual investment in Nuclear and hydrogen fuel cell 2060 – an increased demand based on a 13% GDP growth rate and with significant investment in solar for green hydrogen

on-grid, solar home systems for prosumers, and energy efficiency on the demand side while reducing the usage of diesel/petrol and improving the adoption of gas as a transition fuel. The scenario assumes an investment in energy efficiency (EE) and renewable energy (RE) resources at 30% following the Nationally Determined Contribution (NDC) (2021) by 2030, while more investment in RE and EE according to conditional NDC by considering deliberate fuel-switching efforts and banning the use of diesel/petrol generator by 2045 and 2060, respectively.

The third scenario is the carbon–neutral scenario. Here, the scenario aims to achieve net-zero emissions by investing in nuclear, bioenergy, hydrogen and fuel cells, and are considered beyond the sustainable scenario. To do this, the scenario assumes implementing the net-zero plan according to the ETP (ETP, 2022), including a gradual investment in nuclear, bioenergy and hydrogen fuel cells, and consideration of a significant investment in solar energy for green hydrogen for export in the model period, respectively. The scenarios are summarized in Table 1.

The description of the scenario in Table 1 assumes an electricity demand increase that is based on the gross domestic product (GDP) growth rate in Nigeria. The assumptions of the GDP growth rate are based on the World Bank report, and the analysis from the Energy Commission of Nigeria (ECN) presented in Sambo (2008) and Akanonu, (2019). The scenario assumes that electricity demand would increase at a GDP growth rate of 8% in the BAU, 11% and 13% in the sustainable, and carbon-neutral, respectively. However, the assumption would be found relevant and applied in the model period 2045 and 2060 for the scenario.

Table 2 presents the scenario that explores a distributed generation strategy from the five DisCos. The scenarios are based on assumptions, earlier discussed and it comprises two scenarios based on a regional model for 2030 and 2060. The regional model 2030 describes the gradual phasing out of the use of diesel generators and investment in alternative green technologies, while the regional model 2060 illustrates the replacement of fossil fuel sources with clean alternatives, especially green hydrogen and fuel cells

The carbon-neutral scenario (in Table 2) is subjected to further analysis to reflect a distributed generation strategy. The strategic scenario for distributed energy system planning was done based on the assumption of an aggregated model to explore the role of green hydrogen in the Nigerian power sector via the electricity DisCos. The regional DisCos adopted for this work are selected based on the availability of vast renewable energy resources especially solar and wind in their regions in line with Ohunakin, (2010). The relevant DisCos that cover the regions endowed with renewable energy resources as reported in Ohunakin, (2010), are domiciled in the Northern part of Nigeria including the North-Central,

Table 2 Scenario for distributed energy system planning

Scenario	Description
Regional model 2030	Take into account the gradual phasing out of diesel generators and investment in alternate green energy technology
Regional model 2060	Assumes the replacement of fossil fuel sources with clean alternatives, especially green hydrogen and fuel

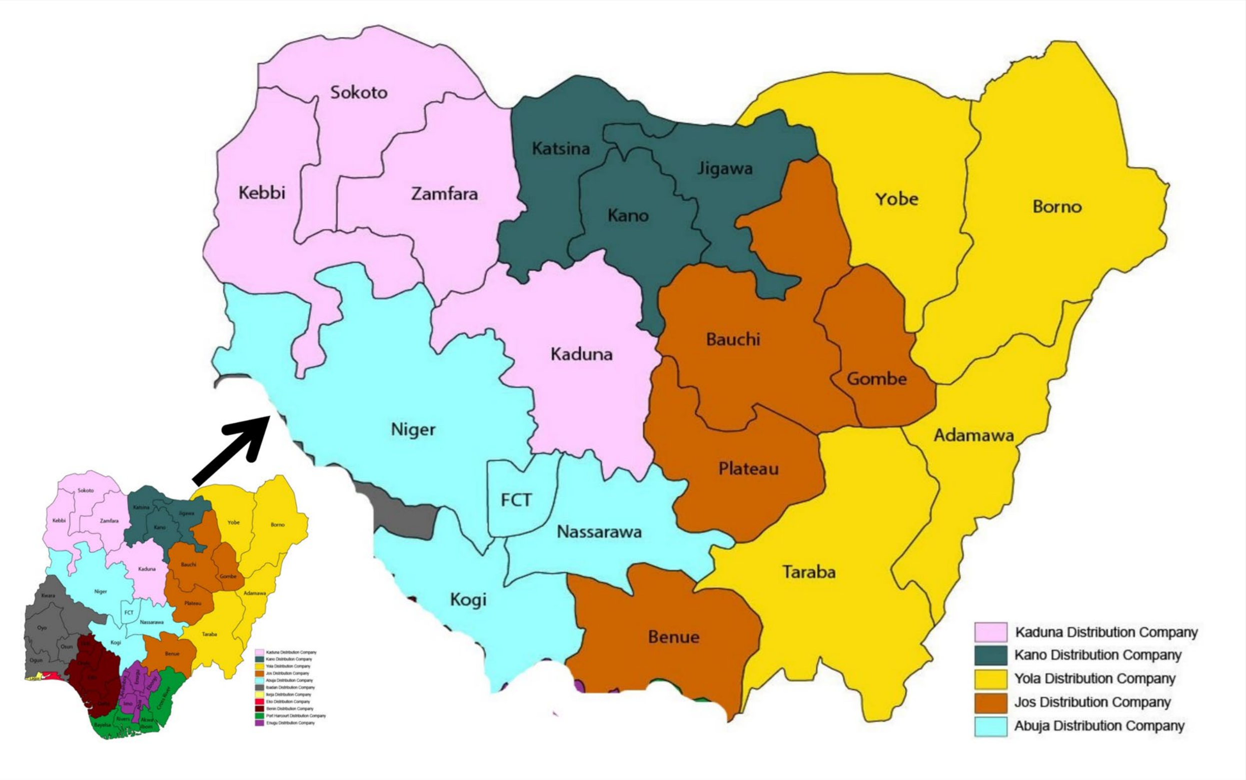

Fig. 6 The five distribution companies DisCos (Source: NERC)

North-East, and North-West (Fig. 6). The DisCos are (i) Kaduna Electricity Distribution Company covering Kaduna, Zamfara, Kebbi, and Sokoto States; (ii) Yola Electricity Distribution Company covering Yobe, Borno, Adamawa and Taraba States; (iii) Abuja Electricity Distribution Company covering, Federal Capital Territory (FCT), Niger, Kogi and Nassarawa States; (iv) Kano Electricity Distribution Company covering Kano, Jigawa and Kastina States; and, (v) Jos Electricity Distribution Company covering Bauchi, Gombe, Plateau and Benue States. The DisCos covers a total of 19 States out of the 36 States of the country.

Results and discussion

The results from the scenario models are presented in this section. The models were developed based on the oemof framework and validated by developing a business-as-usual model as shown in Fig. 7. The Nigerian electricity demand profile utilized for the study was extracted from Toktarova et al. (2019) and then used to benchmark the model. An hourly dispatch model which shows the current power situation in Nigeria is used to validate the model, as shown in Fig. 7.

The result from the model validation shown in Fig. 7, revealed the heavy use of diesel/petrol-powered generator fuel in the country and represents over 60% of the total electricity generated in 2020. This means around 19 GW of power demanded in that year including off-grid and on-grid were met by captive diesel/petrol generator sets. This validation justifies findings in the media reports and the World Bank survey (WB, 2014; Nnodim, 2022). It can be observed from Fig. 7 that less than 30% of the national power demanded was met by a combination of grid-tied gas and hydropower plants. About 20% of the electricity demanded was never met and referred to as the unmet electricity demand, while those met from captive diesel/petrol generator sets are regarded as suppressed demand.

Discussion of the result based on Table 1—net-zero emission strategy

Figure 8 shows the capacity evolution of the business-as-usual scenario across the model period. Exploring the clean energy strategy in the BAU scenario towards a net-zero emissions agenda, Fig. 8 reveals that diesel/petrol-fueled generators will continue to serve as the main supply of power in Nigeria by 2030. Figure 8 further reveals that there would be about a 40% reduction in the usage of diesel-fueled generators by 2045, and there would be no significant usage of captive diesel/petrol

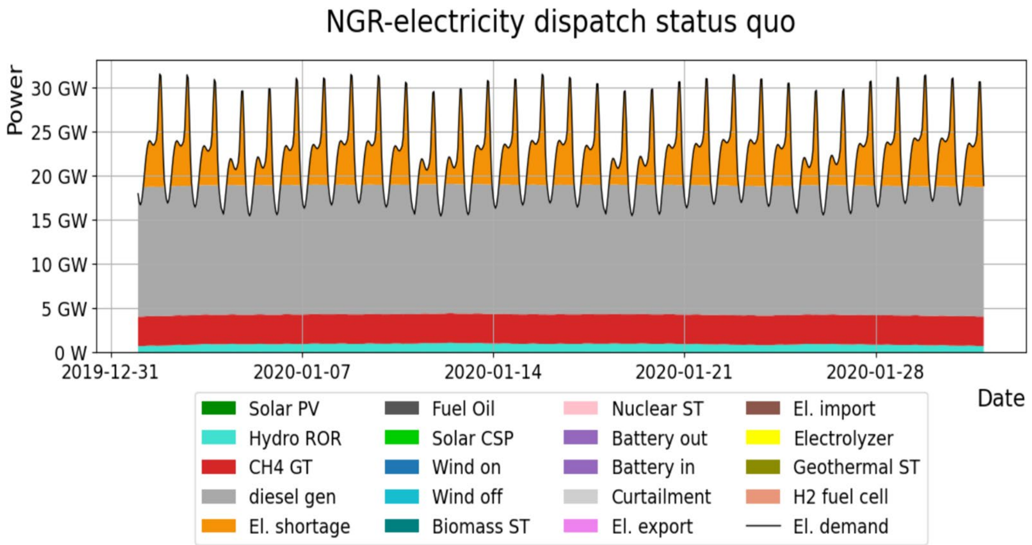

Fig. 7 Model validation via power dispatch–current power situation indicating heavy use of diesel generator, high suppressed and unmet demand

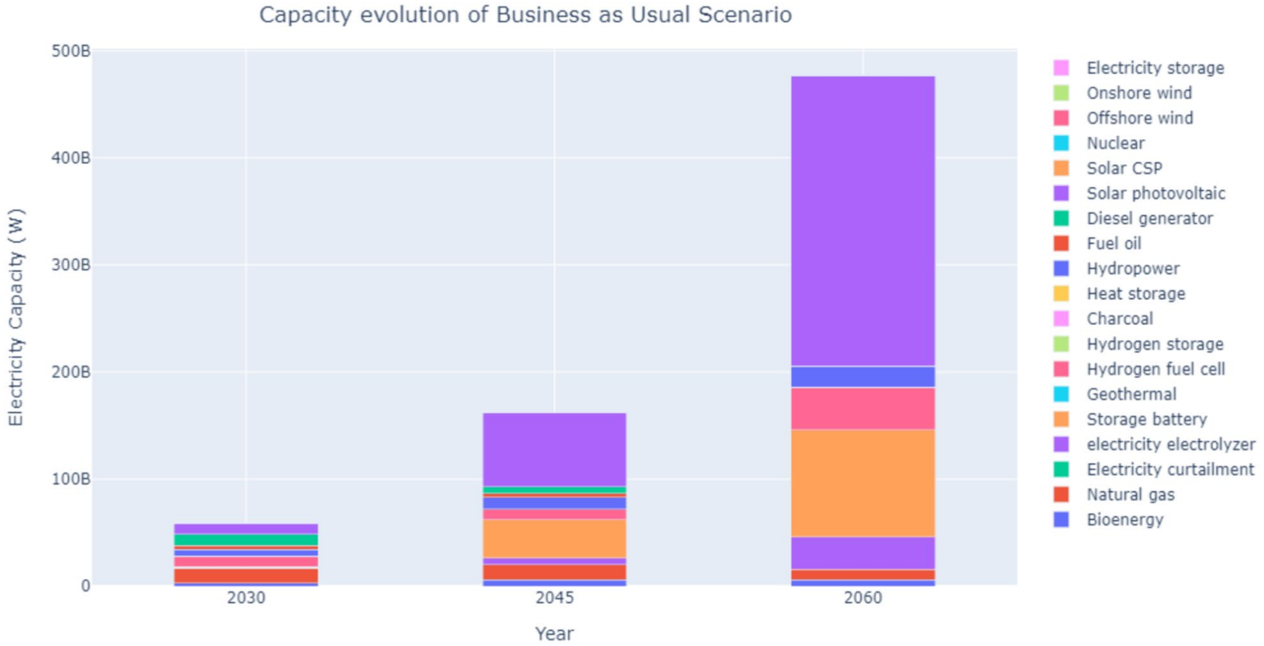

Fig. 8 Evolution of business-as-usual scenario across the model periods

generators by 2060. In the same scenario, natural gas will be a significant part of the energy mix in 2030 and 2045; however, about a 29% reduction in natural gas in the mix by 2060.

Renewable energy sources especially solar photovoltaic (including solar mini-grids and solar home systems) have experienced significant growth from 2030 to 2060, representing the largest single energy source in the BAU scenario. Hydrogen and fuel cells have gained low acceptance in the energy mix, with a constantly low growth rate from 2030 to 2045, but experienced a relative increase in growth rate by 2060. Hydropower has seen a significant growth of about a 50% increase in the BAU scenario. With the bioenergy resource, a sharp rise was experienced from 2030 to 2045, but this became constant by 2060. Due to the rising contribution of renewable energy

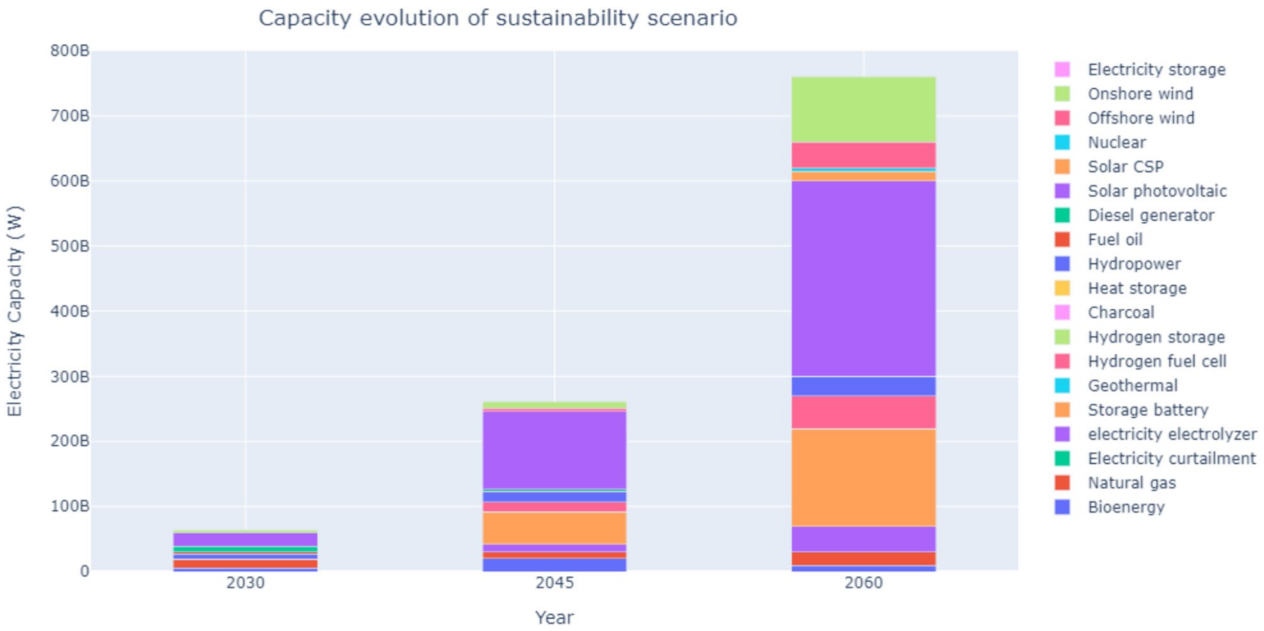

Fig. 9 Evolution of sustainability scenario across the modelling period

in the scenario, electricity storage in battery has been employed and has experienced significant growth from 2045 to 2060.

The scenario has identified that there will be a need for a significantly high level of investment in the power sector moving forward from the base year (i.e. 2020) to achieve such a mix. The scenario shows a significant increase in the share of renewable energy in the energy mix; this suggests that a significantly large share of solar photovoltaic might not be sustainable, due to the large share of storage required and the associated cost. Despite the share of the renewable energy mix and the inclusion of hydrogen and fuel cells, the scenario still employs some level of electricity supplied by diesel generators. These imply that the BAU scenario is not enough of a mix that would eradicate the use of captive diesel/petrol-fueled generator sets, and may not deliver the expected carbon neutrality even in the long term.

The sustainability scenario presented in Fig. 9 shows the model evolution of the energy technology mix over the 2030, 2045, and 2060 periods. In the sustainability scenario, the evolution of fuel oil used in diesel power plants was observed to be marginal in 2030 when compared to the BAU scenario. While natural gas was seen to have met about 20% of energy demand in 2030, power from diesel generators accounted for about 16% of the overall production during the same year, resulting in a reduction in the BAU. In terms of renewable energy share, investment in solar energy was prioritized in 2030 to include both on-grid and off-grid systems; about 20% of electricity was met from solar sources. It is worth noting that onshore wind and bioenergy sources account for about 5% each, of the total mix, while hydropower assumes about 8% of the total mix. Overall, in 2030, the sustainability scenario shows almost an equal mix of both renewable energy and fossil fuel energy sources.

Subsequently, in 2045, the sustainability scenario increased the share of power generation due to increased demand for the period. In this modelling period, the share of fossil fuel sources was marginal and accounted for about 6% of energy generation by source, while renewable energy sources accounted for about 56%, with solar having over 80% of the renewable energy share. Also, generation from hydrogen based on fuel cells accounted for about 7% of total generation, while storage by battery and electricity storage from hydrogen accounted for around 25%. This is likely due to the high share invested in renewable energy, thereby balancing its variable nature. This modelling period (the year 2045) has shown the significance of fuel switching from heavily dependent fossil fuel sources to a wide mix of energy sources.

In the 2060 period shown in Fig. 9, there is no use of captive diesel generators. However, the only fossil fuel source is from gas which accounted for about 2.5% of the total energy mix. Electricity generation from renewable energy sources is highly significant accounting for about 65% of the total electricity generated, while the share of solar PV represents around 62% of total renewable energy sources. Generation from hydrogen fuel cells

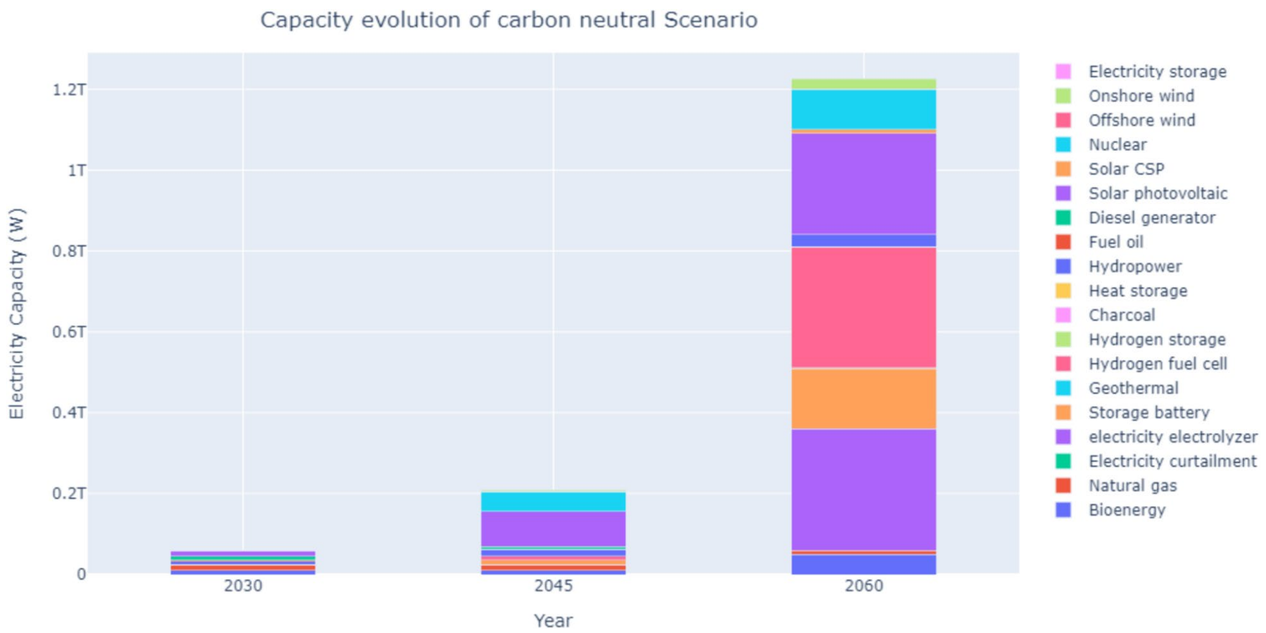

Fig. 10 Evolution of carbon-neutral scenario across the modelling period

accounted for around 6.6%, while electricity storage and battery storage accounted for about 25% of the total electricity supplied.

For the carbon-neutral scenario given in Fig. 10, the 2030 modelling period suggests a substantial energy mix, Natural gas was seen as a fossil fuel source across the modelling period. The 2045 model year shows a similar energy mix to that obtained from another scenario in the same model year; however, the availability of nuclear sources is distinct. For the 2060 model year of the same scenario in Fig. 10, solar, hydrogen, and storage are prioritized in the mix, although the scenario had more electricity demand. Discrepancies in the electricity demand across the modelling period are part of the model assumptions that electricity demand would increase in 2050–2060 based on the GDP growth rate, according to reports from the World Bank and Energy Commission of Nigeria. The carbon–neutral scenario is designed for the highest energy demand.

Discussion of the result based on distributed generation via DisCos (scenario Table 2)

Figure 11 shows hourly dispatched electricity generation capacity in the modelling year 2030 by considering electricity transmission among five DisCos in the Nigerian power sectors. The result from the model is simplified to show generation and distribution flexibilities and to reflect hourly variabilities in electricity generation from renewable energy sources such as wind and solar. As earlier explained, five DisCos have been selected among the eleven DisCos because their zones have higher solar resources compared to the other regions. This would also help manage computation times as simulation could fail with many connections. It is important to note that the demand represented aggregate both on-grid and off-grid power demand.

The ABJ-electricity dispatch represents the Abuja electricity distribution company showing a total demand of about 5.5 GW of power. The ABJ DisCos shows how power demands are met by considering the energy mix. The ABJ DisCos shows that solar and wind have high variability due to their seasonal and hourly availability, while capacity from hydropower and natural gas serves as the base load to cater for the observed variability in the system. It shows no sign of electricity curtailment of storage, and this could be due to the high demand with relatively insufficient capacity. The suppressed demand was catered for by the use of captive diesel/petrol generators. This implies that by 2030 diesel generators will still be dispatched to the Federal Capital Territory (FCT) to make up for the unmet demand.

The JOS electricity dispatch represents the JOS electricity distribution company. It supplies all states shown in Fig. 6. Similar generation is observed as that observed in the Abuja DisCos, although there are more variabilities in the solar PV, and limited natural gas was deployed to the distribution network. There is a large suppressed demand, and unmet demand is observed which is thus expected to be met from diesel/petrol generators. There is no curtailment of electricity.

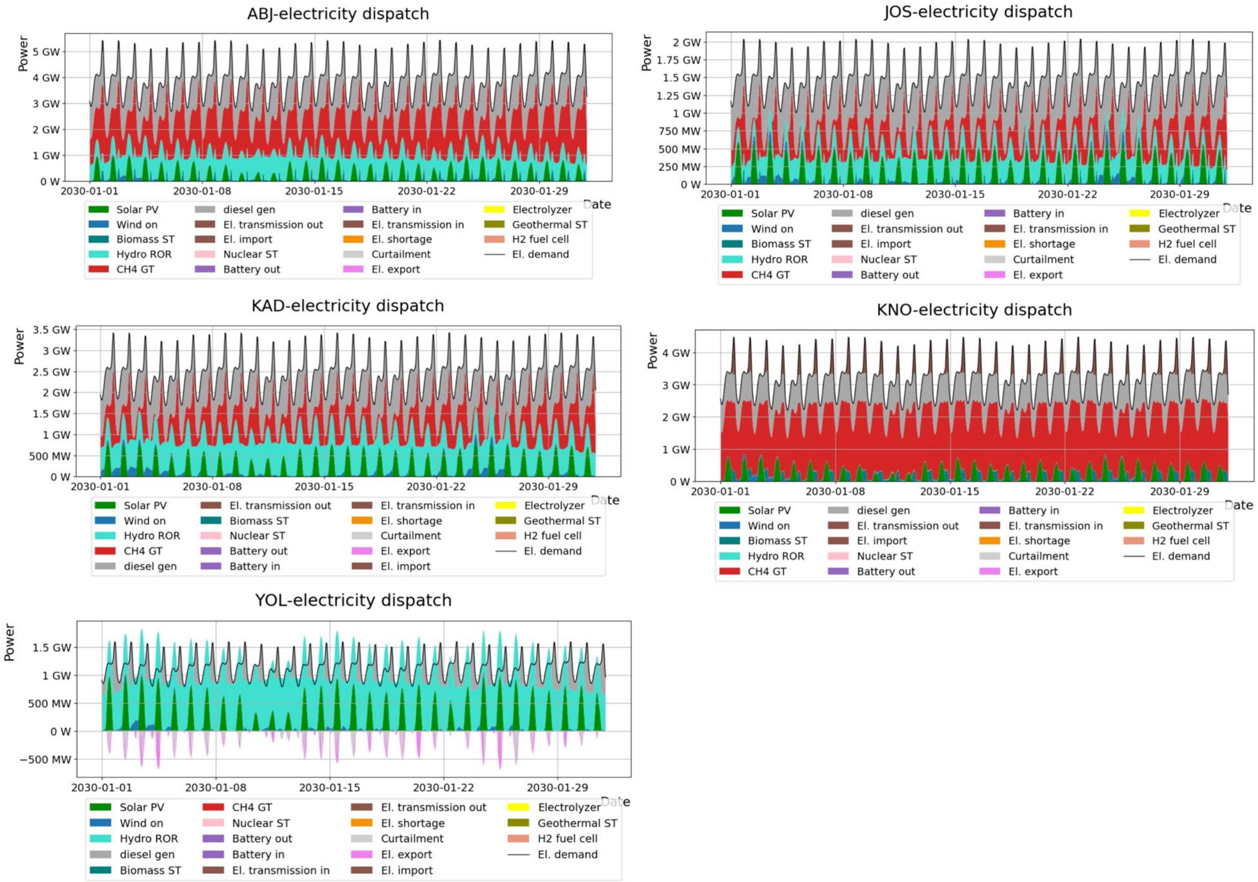

Fig. 11 Hourly electricity dispatched for five DisCos in the Nigeria Power Industry for the month of January, 2030

The Kaduna electricity distribution company represented as KAD-electricity dispatch shows a similar generation trend but more hydropower is dispatched. However, solar and wind generations are observed but not supplied as base load. Although other sources of capacity may have also been generated, this is further explained in later sections. The Kano distribution company shows that more natural gas is dispatched, with little renewable energy and evidence of power import. The result revealed that electricity has been transmitted from other distribution companies to meet some power demand. However, there are still some unmet demands, which are suppressed. The Yola distribution company shows some differences when compared to the other distribution companies in that hydropower was the major supply with supply from solar. It can be observed from Yola DisCos that some electricity was stored and some transmitted to other DisCos including Kano DisCos as shown in Fig. 11. The full scope of generation across the whole scenario may not be very visible in Fig. 11, hence Fig. 12 was plotted to show the capacities across the DisCos.

Figure 12 shows the aggregated capacity according to the distribution companies. It revealed that the Abuja and Yola DisCos have the largest load allocation after Ikeja DisCo and this is because of the high energy demand in that region due to the increased number of allocated States. Figure 12 presents the clear overall outlook of capacities that are dispatched in Fig. 11. It shows that natural gas will be the main fuel by 2030 followed by solar energy resources; this could be due to the current investment made to electrify its rural and underserved areas with solar PV in the form of mini-grid systems and solar home systems. Among other renewable energy sources wind and hydropower are planned to be effectively deployed. Diesel generator shows a significant source of capacity by 2030, while biomass transformed into bioenergy is likely to be among the mix by 2030.

Figure 13 shows hourly electricity dispatched for five electricity distribution companies for January 2060. It can be observed that all the distribution companies show similar characteristics, although with an increase in electricity demand and an increase in generation from solar PV. It was also found that no diesel/petrol-fueled generator

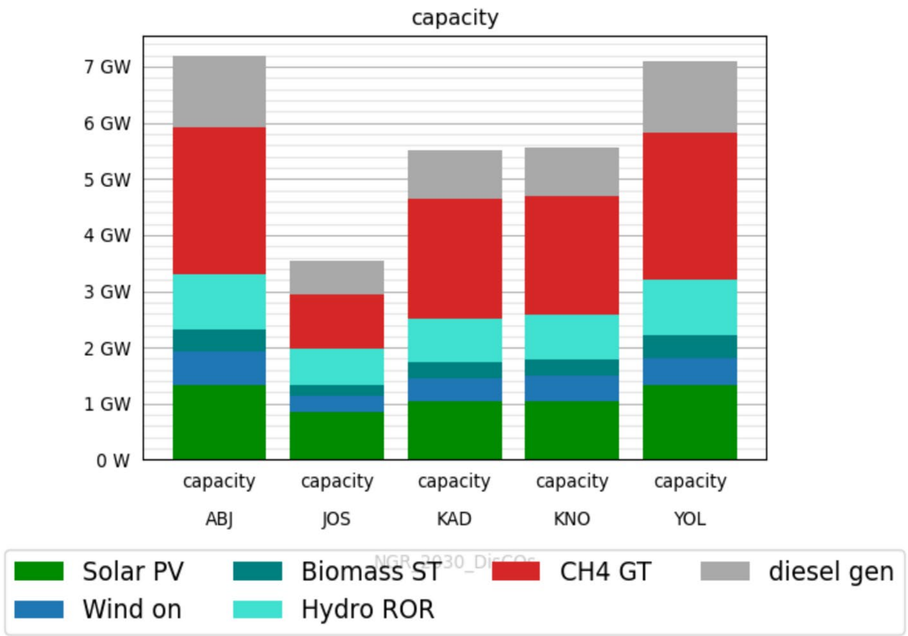

Fig. 12 Aggregated capacity across the Distribution Company by 2030

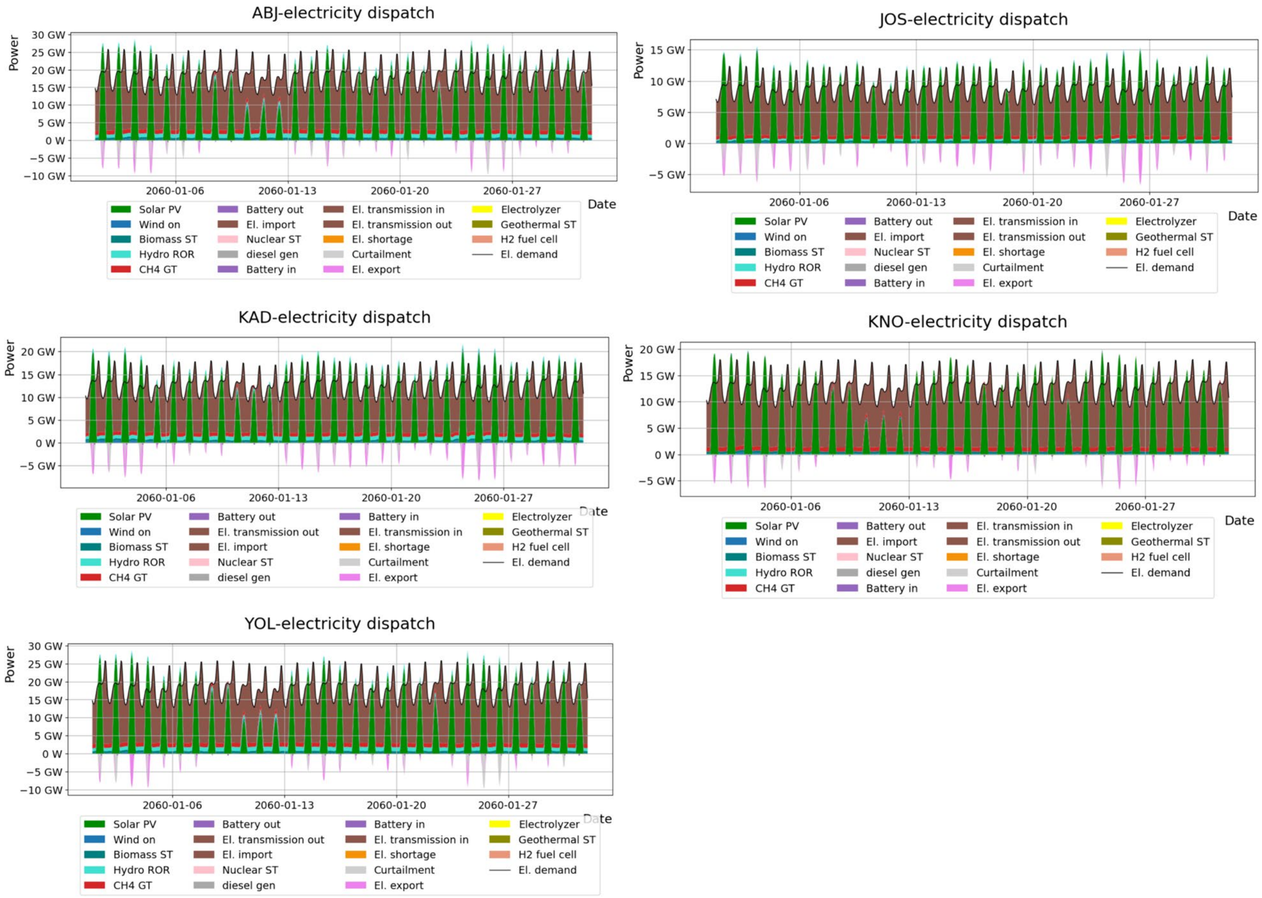

Fig. 13 Hourly electricity dispatched for five DisCos in the Nigeria Power Industry for January, 2060

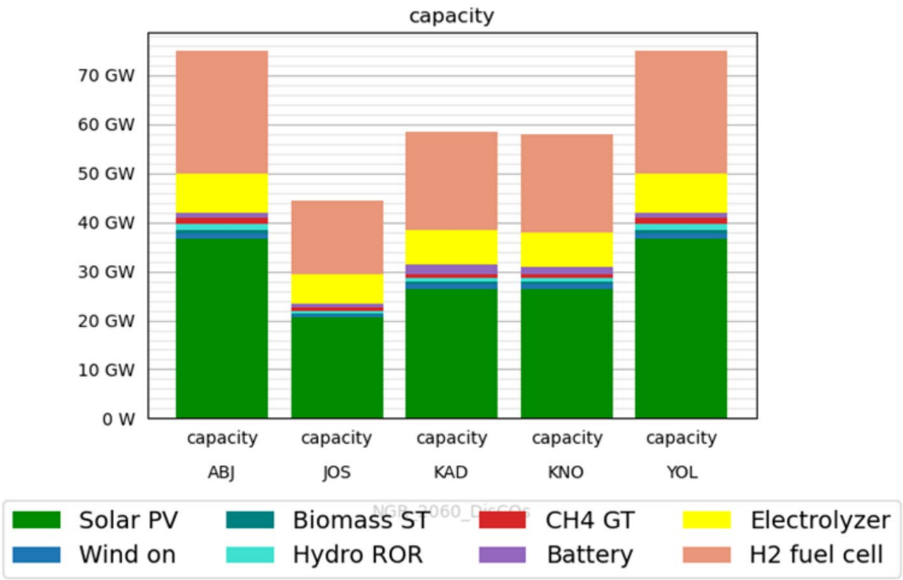

Fig. 14 Aggregated capacity across the Distribution Company by 2060

was dispatched to the system. The figure shows that all suppressed demand has been met through adequate transmissions among the DisCos, while excess electricity was curtailed and exported to DisCos in other regions. Excess electricity generated from renewable energy has been stored and utilized through electrolysis to produce green hydrogen. The fossil fuel source, especially natural gas is marginal. The Kano distribution company does not show the likelihood of dispatching hydropower to meet electricity demand.

In addition, Fig. 13 reveals the outcome for the second scenario described in Table 1 (i.e. the regional model 2060). It assumes the full replacement of all fossil fuel sources with clean alternatives, while green hydrogen takes prominence. The results from the current scenario imply that electricity distributed will play a significant role in meeting unmet/suppressed demand in Nigeria by 2060 (future). This means that power will have to shift from the current centralized scheme and would be generated on a regional basis, based on existing jurisdiction already supplied by the DisCos. While electricity demand is met across all the DisCos, supply from natural gas still serves as the base load. This may be due to the rigorous effort the country has put into natural gas as a transition fuel, which will stay in the country's power mix for a long time. It is also important to note that the electricity dispatched represented in Fig. 13 does not show full variabilities across the whole year, but was simplified to focus on the beginning of the year, i.e. January, as this would provide more clarity and a glimpse of how the system behaves. To present the full system power capacity, Fig. 14 is given to show an aggregated capacity of the five DisCos.

Figure 14 illustrates the contribution from all generations in 2060. It reveals that electrolyzer, hydrogen fuel cell (H_2 fuel cell) and generation from solar PV take over about 80% of the capacities, while capacities from natural gas (CH_4 GT), bioenergy converted from biomass, hydropower from a run of river, and wind (onshore wind), are marginal; they are also low-carbon sources. This implies that natural gas will be a part of the generation mix in the long-term but its contribution is marginal in the modelling period.

Conclusions and policy implications

This section presents deductions from the analysis of an open energy modelling framework. This explores low-carbon energy system modelling for an energy transition plan, and a distributed energy system framework.

It has been shown that Nigeria's electricity demand is huge and rapidly increasing, while a larger part of it is met by captive generation from diesel/petrol generator sets. The persistent use of diesel generator sets would go beyond the current situation, till 2030, 2045, and beyond. As the economy grows at different GDP growth rates, there will be a higher demand for energy infrastructure to meet demand. This will enhance the generation mix while minimizing greenhouse gas emissions. To achieve net-zero emissions reduction targets, natural gas will serve as a transition fuel, which is a major fuel for the short- and medium-term, while solar energy technologies will serve as the most accepted and relevant future driver of the technology mix. Also, the need for green hydrogen fuel cells to be among the technologies that drive Nigeria's green initiative in its net-zero emissions target will be heavily driven by a purposeful and deliberate investment in solar technology. Distributed generation with electricity transmission among the DisCos, would help control excess electricity that would otherwise be wasted or lost. As the country makes net-zero emission plans, adopting a distribution generation approach would better meet demand and enhance the integration of more clean energy technologies into the Nigerian energy mix.

Further, the current study concludes that while energy from natural gas will be a short-, and medium-term driver, solar energy will be the main clean energy initiative that would support the realization of a clean energy transition strategy in the long term. A distributed generation approach would further restrain waste and reduce over-dependence on captive power generation from diesel/petrol generators. Natural gas, being a major future clean fuel in the Nigerian energy transition strategy, should also be well integrated and explored in the residential sector. An integrated assessment of the energy sector and a transition fuel would support robust planning.

The policy implications from the study cut across three thematic areas, which included (i) the cost of electricity in the future; (ii) improved access to electricity; and (iii) emissions reduction in the power sector. The study recommends that attention should be paid to the hydrogen economy for a sustainable electricity price reduction in future, however, population and economic growth will largely increase electricity demand. A price reduction regime through investment in renewable energy considering a distributed-generated system would enhance the proliferation of renewable generation and encourage productive use of electricity. Also, emission reduction would be beneficial to achieve some of the country's Nationally Determined Contributions (NDCs) objectives. The study also recommends that a strategic investment in green hydrogen could be beneficial to attaining the country's power sector NDCs goals. Achieving electricity access is crucial to Nigeria and is a significant part of the NETP, as such distribution energy generation system is one of the most viable ways to achieve sustainable energy access. The study recommends that a deliberate action with a strong political will to invest in a distributed energy generation system, considering already existing infrastructure such as the DisCos framework could support Nigeria's universal energy access in the future.

Finally, to attain sustainable NETP that achieves energy security in the Nigerian power sector, the study recommends that a distributed generation approach among DisCos would support the national net-zero transition plan.

Future studies could consider a range of techno-economic and socio-economic implications of a distributed energy generation system that is based on green hydrogen, including a specific DisCo case study. Also, community-based distributed generation systems could be looked into, that is communities with high proximity should be considered for further analysis as it could suggest a more viable and cost-effective green hydrogen regime. Other oemof and open-sourced energy models could be considered to investigate the energy reality of other developing countries in sub-Saharan Africa to investigate their green hydrogen capability for the mid- and long-term perspective.

Abbreviations

DisCos	Distribution companies
NETP	Nigeria's net-zero transition plan
OEMOF	Open energy modelling framework
SSA	Sub-Saharan African
LOHC	Liquid organic hydrogen carriers
EDG	European green deal
LP	Linear problems
MILP	Mixed-integer linear optimization problems
API	Application programming interface
CHP	Combined heat and power
DC	Direct current
AC	Alternative current
RES	Reference energy system
P2G	Power-to-gas
BAU	Business as usual
REA	Rural electrification agency
RE	Renewable energy
NDCs	Nationally determined contributions
GDP	Gross domestic product
ECN	Energy Commission of Nigeria
FCT	Federal capital territory

Author contributions

BES: conceived the study, developed the methodology, performed the data analysis, conducted data analysis and results, interpreted the results and drew the conclusions, conducted a literature survey, and managed communication with the journal. OSO: supervised the project, helped in developing the methodology, shaped the research objective and aims, also edited the manuscript. YM: supervised the project, helped in developing the methodology and shaping the research objective, and reviewed and edited the manuscript. PB: supervised the project, reviewed and edited the manuscript, guided the project, and assisted in shaping the research objectives. SM: supervised the project, and shaped the research objective and aims. AR: guided the project. All authors gave final approval of the version to be published and agreed to be accountable for all aspects of the work, ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Availability of data and materials

The data and materials used in this study are sourced from publicly available scientific literature, research publications, and reputable online databases and have been referenced below.

Declarations

Competing interests

The authors declare that they have no competing interests, financial or non-financial, that could be perceived as influencing the content or conclusions of this paper.

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References

AbouSeada, N., & Hatem, T. M. (2022). Climate action: Prospects of green hydrogen in Africa. Energy Reports, 8,3873–3890. https://doi.org/10.1016/j.egyr.2022.02.225

Africa's Green Hydrogen Potential (Issue November). (2022). https://climatechampions.unfccc.int/wp-content/uploads/2022/11/AGHA-Green-Hydrogen-Potential-v2_Final.pdf

Akanonu P. (2019). How big is Nigeria's Power Demand (Issue November). https://www.energyforgrowth.org/memo/how-big-is-nigerias-power-demand/

Baye, R. S., Ahenkan, A., & Darkwah, S. (2021). Renewable energy output in sub Saharan Africa. *Renewable Energy, 174*, 705–714. https://doi.org/10.1016/j.renene.2021.01.144

Bhandari, R. (2022). Green hydrogen production potential in West Africa—Case of Niger. *Renewable Energy, 196*, 800–811. https://doi.org/10.1016/j.renene.2022.07.052

Cruz-Soto, J., Azkona-Bedia, I., Cornejo-Jimenez, C., & Romero-Castanon, T. (2024). Assessment of levelized costs for green hydrogen production for the national refineries system in Mexico. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2024.03.316

Di Lullo, G., Giwa, T., Okunlola, A., Davis, M., Mehedi, T., Oni, A. O., & Kumar, A. (2022). Large-scale long-distance land-based hydrogen transportation systems: A comparative techno-economic and greenhouse gas emission assessment. *International Journal of Hydrogen Energy, 47*(83), 35293–35319. https://doi.org/10.1016/j.ijhydene.2022.08.131

Ebii, C. (2023). Green Hydrogen in Nigeria - Potentials and Pitfalls. Heinrich Böll Stiftung | Abuja Office - Nigeria. https://ng.boell.org/en/2023/06/30/green-hydrogen-nigeria-potentials-and-pitfalls

Eriksen, S., Schipper, E. L. F., Scoville-Simonds, M., Vincent, K., Adam, H. N., Brooks, N., Harding, B., Khatri, D., Lenaerts, L., Liverman, D., Mills-Novoa, M., Mosberg, M., Movik, S., Muok, B., Nightingale, A., Ojha, H., Sygna, L., Taylor, M., Vogel, C., & West, J. J. (2021). Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance? *World Development, 141*, 105383. https://doi.org/10.1016/j.worlddev.2020.105383

ETP. (2022). Nigeria energy transition plan. https://energytransition.gov.ng/

Fan, L., Tu, Z., & Chan, S. H. (2021). Recent development of hydrogen and fuel cell technologies: A review. *Energy Reports, 7*, 8421–8446. https://doi.org/10.1016/j.egyr.2021.08.003

Fawzy, S., Osman, A. I., Doran, J., & Rooney, D. W. (2020). Strategies for mitigation of climate change : A review intergovernmental panel on climate change. *Environmental Chemistry Letters, 18*(6), 2069–2094. https://doi.org/10.1007/s10311-020-01059-w

Gielen, D., Saygin, D., Taibi, E., & Birat, J. P. (2020). Renewables-based decarbonization and relocation of iron and steel making: A case study. *Journal of Industrial Ecology, 24*(5), 1113–1125. https://doi.org/10.1111/JIEC.12997

Hart E. W., Laird Carl, Watson Jean-Paul, Woodruff David L., Hackebeil Gabriel A., Nicholson Bethany L., & Siirola John D. (2019). *Pyomo Documentation*.

HFW. (2022). NH_3 news: is ammonia the future of long-distance hydrogen transport? In *Holman Fenwick Willan LLP*. https://www.zerocarbonshipping.com/energy-carriers/e-ammonia/

Hilpert, S., Stephan, G., Kaldemeyer, C., Krien, U., & Pleßmann, G. (2017). Addressing energy system modelling challenges: The contribution of the open energy modelling framework (oemof). Preprint. https://doi.org/10.20944/preprints201702.0055.v1

Hilpert, S., Kaldemeyer, C., Wiese, F., & Plessmann, G. (2017). A qualitative evaluation approach for energy system modelling software—Case study results for the open energy modelling framework (Oemof). Preprint, August, 1–19. https://doi.org/10.20944/preprints201708.0069.v1

Hilpert, S., Kaldemeyer, C., Krien, U., Günther, S., Wingenbach, C., & Plessmann, G. (2018). The open energy modelling framework (oemof)—A new approach to facilitate open science in energy system modelling. *Energy Strategy Reviews, 22*, 16–25. https://doi.org/10.1016/j.esr.2018.07.001

IEA. (2020). The oil and gas industry in energy transitions. In *The International Energy Agency. World Energy Outlook special report*. https://doi.org/10.1787/aef89fbd-en

IEA. (2021). Net Zero by 2050: A roadmap for the global energy sector. In *International Energy Agency*. https://www.iea.org/reports/net-zero-by-2050

IEA. (2022). Global hydrogen review. *International Energy Agency*. https://doi.org/10.1787/a15b8442-en

IPCC. (2018). Global warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,. In *An IPCC Working Group I Technical Support Unit*. https://doi.org/10.1002/9780470996621.ch50

IRENA. (2022). *Hydrogen*. https://www.irena.org/Energy-Transition/Technology/Hydrogen

IRENA. (2023). *Renewable Energy Roadmap: Nigeria*. https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/Jan/IRENA_REMap_Nigeria_2023.pdf?rev=c66c5ded17af4a839b30d1c047f7141e

Kabir, M. M., Akter, M. M., Huang, Z., Tijing, L., & Shon, H. K. (2023). Hydrogen production from water industries for a circular economy. *Desalination, 554*(February), 116448. https://doi.org/10.1016/j.desal.2023.116448

Kobina, K. M., & Stephanie, G. (2022). *Green Hydrogen: A key investment for the energy transition*. World Bank. https://blogs.worldbank.org/ppps/green-hydrogen-key-investment-energy-transition

Krien, U., Schönfeldt, P., Launer, J., Hilpert, S., & Kaldemeyer, C. (2020a). oemof.solph—A model generator for linear and mixed-integer linear optimisation of energy systems. *Software Impacts, 6*, 100028. https://doi.org/10.1016/j.simpa.2020.100028

Krien, U., Schönfeldt, P., Launer, J., Hilpert, S., & Kaldemeyer, C. (2020b). oemof.solph—A model generator for linear and mixed-integer linear optimisation of energy systems oemofsolph—A model generator for linear and mixed-integer linear optimisation of energy systems. *Software Impacts, 6*, 100028. https://doi.org/10.1016/j.simpa.2020.100028

Le, T. H., Kim, M. P., Park, C. H., & Tran, Q. N. (2024). Recent Developments in Materials for Physical Hydrogen Storage: A Review. Materials, 17(3). https://doi.org/10.3390/ma17030666

Maduabuchi, C. M. (2004). Surface and groundwater resources monitoring and management in Nigeria. In *A presentation at the United Nations/Austria/Esa Symposium On Space Applications For Sustainable Development*. https://www.unoosa.org/documents/pdf/psa/activities/2004/Graz/22.pdf

Man, J., Ma, T., Yu, Y., & Ren, H. (2024). Levelized costs and potential production of green hydrogen with wind and solar power in different provinces of mainland China. Journal of Renewable and Sustainable Energy, 16(2), 25902. https://doi.org/10.1063/5.0183511

mcdcc Newsom, C. (2012). Renewable Energy Potential in Nigeria: Low-carbon approaches to tackling Nigeria's energy poverty. In *International Institute for Environment and Development* (Vol. 2012, Issues 1–26). http://ec.europa.eu/world/

Michoud, B., & Hafner, M. (2021). *Financing clean energy access in Sub-Saharan Africa: Risk mitigation strategies and innovative financing structures*. https://www.dropbox.com/s/wprd5hv0eavycyb/978-3-030-75829-5.pdf?dl=0

Molloy, P. (2019). Hydrogen fuel cell trucks can decarbonise heavy transport. In *Energy Post*. https://energypost.eu/hydrogen-fuel-cell-trucks-can-decarbonise-heavy-transport/

NDC. (2021). *The Federal Republic of Nigeria: Nationally Determined Contribution*.

Nnodim, O. (2022). *40% Nigerian households use generators, spend $14bn on fuel*. Punch Online. https://punchng.com/40-nigerian-households-use-generators-spend-14bn-on-fuel-report/

Oemof-Team. (2020). *oemof Documentation*.

Ohunakin, O. S. (2010). Energy utilization and renewable energy sources in Nigeria. *Journal of Engineering and Applied Sciences., 5*(2), 171–177.

Oteze, G. E. (1981). Water resources in Nigeria. *Environmental Geology, 3*(4), 177–184. https://doi.org/10.1007/BF02473501

Panchenko, V. A., Daus, Y. V., Kovalev, A. A., Yudaev, I. V., & Litti, Y. V. (2023). Prospects for the production of green hydrogen: review of countries with high potential. *International Journal of Hydrogen Energy, 48*(12), 4551–4571. https://doi.org/10.1016/j.ijhydene.2022.10.084

Qureshi, F., Yusuf, M., Arham Khan, M., Ibrahim, H., Ekeoma, B. C., Kamyab, H., Rahman, M. M., Nadda, A. K., & Chelliapan, S. (2023). A State-of-The-Art Review on the Latest trends in Hydrogen production, storage, and transportation techniques. Fuel, 340(January), 127574. https://doi.org/10.1016/j.fuel.2023.127574

Ramachandran, R., & Menon, R. K. (1998). An overview of industrial uses of hydrogen. *International Journal of Hydrogen Energy, 23*(7), 593–598. https://doi.org/10.1016/s0360-3199(97)00112-2

REA. (2016). *Federal Republic Of Nigeria Rural Electrification Strategy And Implementation Plan (Resip) Federal Ministry Of Power , Works And Housing* (Issue July).

Roche, M. Y., Verolme, H., Agbaegbu, C., Binnington, T., Fischedick, M., & Oladipo, E. O. (2020). Achieving sustainable development goals in Nigeria's power sector: Assessment of transition pathways. *Climate Policy, 20*(7), 846–865. https://doi.org/10.1080/14693062.2019.1661818

Roeb, M., Brendelberger, S., Rosenstiel, A., Agrafiotis, C., Monnerie, N., Budama, V., & Jacobs, N. (2020). Hydrogen as a foundation of the energy transition Part 1: Technologies and perspectives for a sustainable and economical hydrogen supply. In DLR, Institute for Solar Research. https://elib.dlr.de/137796/

Sambo, A. (2008). Matching electricity supply with demand in Nigeria. In *International Association for Energy Economics* (Issue 4, pp. 32–36). http://expertscolumn.com/content/matching-electricity-supply-demand-nigeria

Shari, B. E., Madougou, S., Ohunakin, O. S., Blechinger, P., Moumouni, Y., Ahmed, A., & Tukur, Y. (2023). Exploring the dynamics of stakeholders' perspectives towards planning low-carbon energy transitions: A case of the Nigerian power sector. *International Journal of Sustainable Energy, 42*(1), 209–235. https://doi.org/10.1080/14786451.2023.2186147

Štuller, P., Drábik, P., & Vernerová, D. (2022). Green hydrogen production in Slovakia as part of the circular economy. *Central And Eastern Europe In The Changing Business Environment*, 115–127. https://doi.org/10.18267/pr.2022.kre.2454.9

Toktarova, A., Gruber, L., Hlusiak, M., Bogdanov, D., & Breyer, C. (2019). Electrical power and energy systems long term load projection in high resolution for all countries globally. *Electrical Power and Energy Systems, 111*(March), 160–181. https://doi.org/10.1016/j.ijepes.2019.03.055

USAID. (2021). *Nigeria Water Resources Profile Overview*. https://winrock.org/wp-content/uploads/2021/08/Nigeria_Country_Profile_Final.pdf

van der Spek, M., Banet, C., Bauer, C., Gabrielli, P., Goldthorpe, W., Mazzotti, M., Munkejord, S. T., Røkke, N. A., Shah, N., Sunny, N., Sutter, D., Trusler, J. M., & Gazzani, M. (2022). Perspective on the hydrogen economy as a pathway to reach net-zero CO_2 emissions in Europe†. *Energy and Environmental Science, 15*(3), 1034–1077. https://doi.org/10.1039/d1ee02118d

Wendt, D., Knighton, L., & Boardman, R. (2022). High Temperature Steam Electrolysis Process Performance and Cost Estimates (Issue INL/RPT-22-66117-Rev000). https://www.osti.gov/biblio/1867883%0A https://www.osti.gov/servlets/purl/1867883/

WorldBank. (2014). Diesel power generation: Inventories and black carbon emissions in Nigeria. *World Bank Report*. https://doi.org/10.1596/28419

Yadav, D., & Banerjee, R. (2020). Net energy and carbon footprint analysis of solar hydrogen production from the high-temperature electrolysis process. Applied Energy, 262, 114503.https://doi.org/10.1016/j.apenergy.2020.114503

Yang, M., Hunger, R., Berrettoni, S., Sprecher, B., & Wang, B. (2023). A review of hydrogen storage and transport technologies. Clean Energy, 7(1), 190–216. https://doi.org/10.1093/ce/zkad021

Yohannes, B., & Diedou, A. (2022). *Green hydrogen: A viable option for transforming Africa's energy sector|Africa Renewal*. AfricaRenewal. https://www.un.org/africarenewal/magazine/july-2022/green-hydrogen-viable-option-transforming-africas-energy-sector

Gorre, J., & Nweke-Eze, C. (2023). Green Hydrogen for Decentralized Energy Applications in Nigeria, Advisory Report. *Deutsche Gesellschaft Fur Internationale Zusammenarbeit (GIZ) Gmbh*, 1–23.

Halloran, C., Leonard, A., Salmon, N., Müller, L., & Hirmer, S. (2024). GeoH2 model: Geospatial cost optimization of green hydrogen production including storage and transportation. *MethodsX*, 12(102660). https://doi.org/10.1016/j.mex.2024.102660

Hydrogen Council. (2020). *Path to hydrogen competitiveness A cost perspective*. https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

Oemof-B3. (2023). *GitHub - rl-institut/oemof-B3: An open-source energy system model for Brandenburg/Berlin. GitHub - Rl-Institut*. https://github.com/rl-institut/oemof-B3

Prognos. (2020). *Kosten und Transformationspfade für strombasierte Energieträger Kosten und Transformationspfade für strombasierte Energieträger*.

Schelling, K. (2023). *Green Hydrogen to Undercut Gray Sibling by End of Decade | BloombergNEF. BloombergNEF*; BloombergNEF. https://about.bnef.com/blog/green-hydrogen-to-undercut-gray-sibling-by-end-of-decade/

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