Energy for Sustainable Development 88 (2025) 101810

Contents lists available at ScienceDirect

Energy for Sustainable Development

journal homepage: www.journals.elsevier.com/energy-for-sustainable-development

Nigeria's climate responsiveness: Navigating energy-climate and techno-financial conundrums in the low-carbon energy transition

Godwin Oghenebrozie Atedhor

Department of Geography and Regional Planning, University of Benin, Benin City, Nigeria

ARTICLE INFO

Keywords:
Low-carbon energy
Energy transition
Techno-financial challenges in energy transition
GHG reduction strategies
Climate change mitigation
Unlocking renewable energy
Developing economies

ABSTRACT

This paper reviewed contexts of climate responsiveness in Nigeria's energy sector, focusing on energy-climate complexities, techno-financial challenges in the low-carbon energy transition (ET), adopting a narrative review approach. Findings reveal that Nigeria's climate responsiveness in the energy sector is marked by contradictory paths–promoting a low-carbon ET while simultaneously expanding fossil fuel development amid rising trend in CO_2 emissions. The technological challenges that limit the country's low-carbon ET include old grid infrastructures, poor grid maintenance, inadequate generation and transmitting capacity, shortage of critical CC mitigation technologies, reliance on imported technologies, poor integration of RE into national grid, poor research, development, and innovation, and inadequate skilled manpower. Financial threats to the low-carbon ET include mounting debt burden, poor fiscal policy implementation, fossil energy-skewed investment, lack of investment guarantee, perceived high-risk of RE investment, weak domestic-driven funding mechanisms, corruption, poor harnessing of funding opportunities, and high initial cost of low-carbon technologies. The paper concludes that without bold and well-coordinated techno-financial measures, Nigeria's low-carbon ET is likely to remain sluggish and far from its intended targets. Proposed pathways to mitigating the technological challenges include grid modernization and decentralization, advancing research, development and innovation, promotion of energy efficient development, and facilitation of local manufacturing and technological transfer, while financial strategies for low-carbon ET include adoption of innovative financing models, such as PPPs, cooperatives, and third-party ownerships, promotion of cost reduction strategies, de-risking RE investments, adoption of carbon pricing and subsidy reforms, canvassing for debt forgiveness, and leveraging international climate financing. The insights provided could foster replicable climate-friendly energy development while simultaneously enhancing energy access in developing countries with similar energy trajectories.

Introduction

Climate change (CC) remains an existential threat of unprecedented magnitudes, posing a tough and escalating challenges that endanger our planet, ecosystems, and societies, requiring urgent, collective, and transformative action. Human-caused CC is exacerbating extreme weather events, exacting widespread damages worldwide, with vulnerable populations disproportionately affected, and as global temperatures rise, the severity and frequency of multiple climate-related hazards will increase concurrently (Intergovernmental Panel on Climate Change, IPCC, 2023). It is a prevailing tangible reality, constituting immediate physical and financial risks to investments and businesses (In et al., 2022).

Unsustainable energy use and consumption patterns are key drivers of rising greenhouse gas (GHG) emissions (IPCC, 2023), the main culprit of CC. Rising global energy demand has led to increased GHG emissions (Nwali et al., 2024). The growing recognition of the need to address CC has highlighted the harmful environmental effects of fossil fuel-based energy, prompting intense scrutiny of the energy sector, which is the main source of carbon emissions (Elum & Momodu, 2017), increasingly engendering the need to switch to environment-friendly energy options (Kilinc-Ata & Dolmatov, 2023; Kumar & Majid, 2020; Mutezo & Mulepo, 2021; Wenga et al., 2023; Yusuf et al., 2020). However, while preceding and contemporary greenhouse gas (GHG) emissions are majorly blamed on developed economies, it is foreseen that expected releases will come from budding economies as they match toward industrialization (Elum & Momodu, 2017).

Although countries across sub-Saharan are reportedly faced with low energy generation and access (Nsafon et al., 2023; Tomala et al., 2021), projected increase in population and income in the region is expected to

E-mail address: godwin.atedhor@uniben.edu.

https://doi.org/10.1016/j.esd.2025.101810
Received 2 May 2025; Received in revised form 2 August 2025; Accepted 9 August 2025
Available online 18 August 2025

increase demand for energy services (Dagnachew et al., 2020). The significant proportion of sub-Saharan Africa in the worldwide population could make the realization of global energy net-zero emission unattainable without greater commitment by countries in the region (Muktar et al., 2023). Nigeria accounts for 15 % of the population of Africa (Schneider, 2020) and the country is projected to have a total population of over 400 million by 2050 (Dioha et al., 2019) amid increasing consideration to enhance energy generation and access by governments (Ackah et al., 2019). Over half of Nigeria's population has no access to power (Dodo et al., 2021), highlighting that the actualization of the SDGs in Nigeria depends significantly on energy (Adewuyi et al., 2020).

Nigeria is legally bound to achieve a 20 % unconditional emission reduction by 2030, rooted in the principle of Common but Differentiated Responsibility (FGN, 2021a; Noah, 2024). A rapid transition to clean energy is crucial to meet climate targets, but RE firms, particularly in low-and middle-income countries, face significant financial, policy, and economic obstacles that hinder investment in low-carbon technologies (Isah et al., 2023). Nigeria's transition to a low-carbon economy, driven by RE, is vital to reduce fossil fuel reliance, but it requires overcoming barriers through a coordinated and flexible approach (Okoh & Okpanachi, 2023). Despite prevailing uncertainties, Nigeria has compelling drivers of low-carbon energy which include huge RE potential, viable market, and vast employment openings in the RE sector (Ogbonna et al., 2023). However, decarbonization approaches, industrial processes, and investment goals influence the transformation of Nigeria's energy sector (Okoh & Okpanachi, 2023).

Balancing economic growth with environmentally friendly practices to ensure a sustainable future remains a daunting global challenge (Xia et al., 2023). A shift from fossil fuels to cleaner energy sources necessitates bold and credible actions by countries to drastically reduce GHG emissions and reinforce the resilience of their energy systems (Ajayi et al., 2022; Shari et al., 2023). Substantial investments and significant funding are required to combat CC and transition to a low-carbon economy (García et al., 2023). CC could pose detrimental long-term impact on Nigeria's economy growth, warranting proactive policies that prioritize climate resilience and sustainability (Arogundade et al., 2024). Climate stabilization needs significant investments in low- and zero-carbon technologies, particularly in emerging economies and developing economies, but access to affordable financing differs greatly between states (Calcaterra et al., 2024). Current country pledges and policies fall short of limiting global warming to 1.5 °C or 2 °C, with significant gaps in emissions reduction and insufficient climate finance (IPCC, 2023). The situation is particularly dire for developing countries, especially in sub-Saharan Africa, where the devasting impacts of CC are exacerbated by technological gaps coupled with heavy debt burdens.

Although energy development in in Nigeria and sub-Saharan Africa has been widely studied, particularly through the lens of SDG 7, there remains a significant gap in understanding climate responsiveness (SDG 13), especially regarding the technological and financial challenges to low-carbon ET. This paper therefore seeks to appraise Nigeria's climate responsiveness by conducting a literature review to uncover the contexts of energy-climate, technological, and financial complexities shaping the country's low-carbon ET. Additionally, the paper offers transformative pathways for overcoming technological and financial barriers to Nigeria's low-carbon ET. The insights from the review could inform evidence-based policies and strategic interventions to accelerate the country's low-carbon ET, with broader applicability to other developing economies following similar trajectories.

Methodology

Geographical setting

Nigeria lies in the tropics from latitude 4° and 14° North and between longitude 4° and 15° East, with a total land area of 923, 768 km^2. The country's estimated population stands at approximately 237 million with annual growth rate of 2.08 % as at April 21, 2025 (Worldometer, 2025). It is the most populous black nation. The country is endowed with diverse energy resources such as coal, crude oil, hydro, solar and wind. Despite the varied energy resources which abound in the country, it is suffers persistent energy shortage. Crude oil export makes up over 80 % of its export earnings. Nigeria is the 8th biggest exporter of crude oil globally (Aderounmu et al., 2021). Despite being a major crude oil producing and exporting country, it depends on imported refined petroleum products for most of its domestic energy requirements due to unproductive state of its refineries, until recently when the Dangote Refineries, the largest refinery in Africa started operation. The country falls within lower middle-income economies (The World Bank Group, 2023).

Review methodology

This study carried out desk review of climate responsiveness in Nigeria's energy sector, with a focus on energy-climate, technological and financial challenges, and low-carbon ET pathways adopting a narrative review approach. In addition to being rooted in screening and synthesis of relevant literature, the review also provides data-driven insights. Relevant materials were sourced through searches conducted on Google, Google Scholar, ScienceDirect, and ResearchGate (Fig. 1). The resources appraised in this study essentially comprise journal articles, conference proceedings, government policies, federal government technical reports, technical report, and data sourced from databases. The literature search focused on five thematic areas: energy-climate dynamics, RE deployment, technological, financial challenges, and pathways to low-carbon ET. For energy-climate dilemma, search terms targeted Nigeria's fossil-associated CO_2 emissions, ET, and RE development (e.g., 'fossil fuel energy' AND 'Nigeria', and renewable energy development' AND 'Nigeria'). For technological challenges, terms such as 'renewable energy technologies' AND 'Nigeria', 'energy infrastructure' AND 'climate change' AND 'Nigeria', and 'technological barriers' AND 'Nigeria' AND 'low-carbon transition' AND 'Nigeria' were used. For financial challenges, search terms included 'climate finance' AND

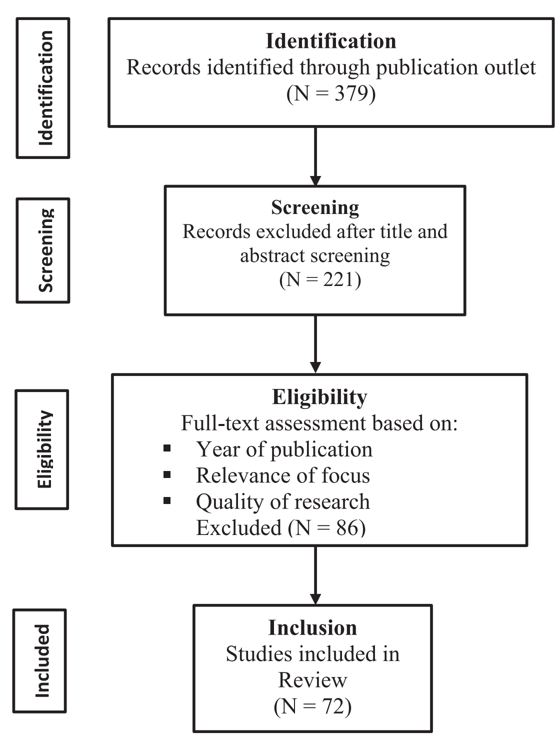

Fig. 1. Flowchart of materials selection process.

'Nigeria', 'investment barriers' AND 'renewable energy' AND 'Nigeria' AND 'green finance' AND 'Nigeria's energy sector'. A total of 379 materials were initially identified and retrieved based on publication outlet. After screening titles and/or abstracts, 221 materials were excluded for irrelevance to the focus of this review. The remaining 158 materials were subjected to further eligibility screening (full-text), where 85 were excluded based on factors such as publication year (outside 2019–2025), irrelevance of focus, and quality concerns. This process resulted in 72 materials being included in the final review. The materials reviewed are thematically presented in Table 1. Because of multidimensionality of focus, some of the reviewed materials cut across multiple themes. Journal articles and proceedings published by Elsevier, Springer, Taylor and Francis, Wiley, Sage, Cambridge University Press, IOP, and MDPI (Fig. 2.), basically formed material included in addition to government policies, reports, and historical data. Policy-related materials reviewed include Nigeria's First Nationally Determined Contribution, National Renewable Energy and Energy Efficiency Policy (NREEEP), National Energy Policy, National Policy on Climate Change and CAT Climate Governance Series. In addition, historical data including Nigeria's fossil fuel energy supplies, CO_2 emissions from fuel combustion, renewable electricity generation, and renewable share of electricity spanned 20-year (2001–2020) were sourced from relevant databases.

Table 1
Materials thematically reviewed.

Theme	Reference
Fossil-energy-CO_2 dynamics	Obada et al. (2024), Tunde et al. (2022), Olujobi et al. (2023), Akujor et al. (2022), Salakhetdinov and Agyyeno (2020), Roche et al. (2020), Okedere and Oyelami (2021), Afinotan (2022) Nwachukwu et al. (2024) IEA (n.d.-a), IEA (n.d.-b), Isihak (2023), Alabi et al. (2023), Amakom et al. (2022), Roy et al. (2023), Bebeteidoh et al. (2020), Odekanle et al. (2021), Onakpohor et al. (2020)
RE deployment	Adedokun et al. (2025), Elum and Momodu (2017), Esan et al. (2019), Bhuiyan et al. (2022), Olujobi et al. (2023), Obada et al. (2024), Chanchangi et al. (2022), Ibrahim et al. (2021), CAT (2022), Nwachukwu et al. (2024), Nwankwo et al. (2024), Okoh and Okpanachi (2023), CountryEconomy.com, Sasu (2024), Ajayi et al. (2022), Ugwu et al. (2022), IEA (2024), Federal Government of Nigeria (2015)
Technological challenges	Oyedepo et al. (2018), Babayomi et al. (2022), Adewuyi et al. (2020), Roy et al. (2023), Adoghe et al. (2023), IEA (2024), Kabeyi and Olanrewaju (2023), Nwangwu et al. (2024), Adeyanju et al. (2020), Dioha et al. (2025), Adedokun et al. (2025), Nwaiwu (2021), Ozoegwu and Akpan (2021), Adebayo et al. (2021), Obada et al. (2024), Abe and Azubuike (2024), Obada et al. (2024), Edomah et al. (2021), Nwachukwu et al. (2024), Akujor et al. (2022), Nwali et al. (2024), Energy Commission of Nigeria (2018), Adepoju et al. (2022).
Financial barriers	FGN (2021b), Debt Management Office Nigeria (2025), Roy et al. (2023), Chipangamate and Nwaila (2024), Adebayo et al. (2021), Isah et al. (2023), Adeyanju et al. (2020), Ogbonna et al. (2023), Obada et al. (2024), Dimnwobi et al. (2022), Mohammad et al. (2023), Abdulkarim (2023) Mutarindwa et al. (2024), Nyarko et al. (2023)
Technological low-carbon energy pathways	Abe and Azubuike (2024), Kabeyi and Olanrewaju (2023), Oyedepo et al. (2018), Gungah et al. (2019), Okoh and Okpanachi (2023), Farghali et al. (2023), Roche (2023), Okoh and Okpanachi (2023), Nwali et al. (2024), Shari et al. (2024), Ogbonna et al. (2023), Okere et al. (2019), Nwozor et al. (2021), Jekayinfa et al. (2020), Azuazu et al. (2023)
Financial pathways to low-carbon energy	Obada et al. (2024), Nduka (2022), Isah et al. (2023), Kaze et al. (2025), Adebayo et al. (2021), Adeyanju et al. (2020), Dimnwobi et al. (2022), Dorband et al. (2022), Babatunde et al. (2023)

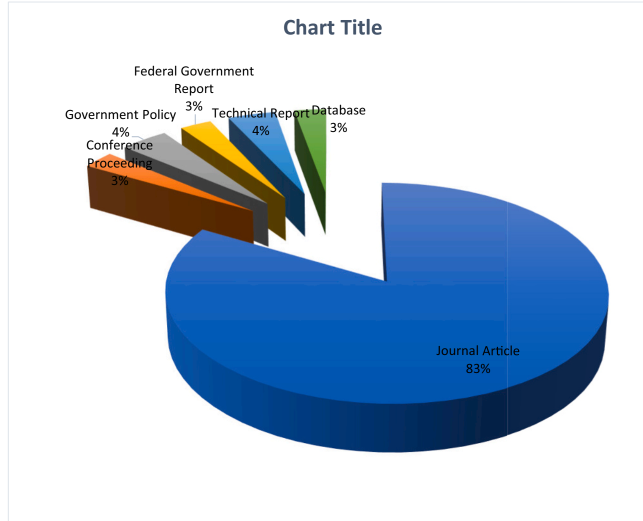

Fig. 2. Sources of materials.

The narrative approach facilitated a flexible and descriptive synthesis of relevant literature. The materials selected were subjected to thematic analysis, allowing for the identification and organization of recurring themes across the literature. The analysis focused on categorizing insights under five key thematic areas: fossil energy-CO_2 dynamics, RE deployment, technological challenges, financial barriers and pathways to low-carbon ET.

Results and discussion

Nigeria's fossil energy supplies, fossil-associated CO_2 emissions and ET

Human activities, particularly in energy production and use, are primary sources of GHG emissions that contribute to CC (Obada et al., 2024). CO_2 emissions are responsible for over 70 % of greenhouse effect (Tunde et al., 2022). While GHGs, such as methane (CH_4) and nitrous oxide (NO_2), contribute to global warming, CO_2 emissions are the most significant and widely reported. CO_2 emissions are directly correlated with energy consumptions (Abeydeera et al., 2019; Chaudhury et al., 2023; Ghazouani et al., 2020; Yadzi & Dariani, 2019). Fig. 3 shows the annual trend of Nigeria's fossil energy supplies and fossil-associated CO_2 emissions (2001–2022). While fossil energy supplies rose from about 772 thousand Tj in 2001 to above 1.7 million Tj in 2022, fossil-associated CO_2 emissions increased from about 50 Mt. CO_2 in 2001 to

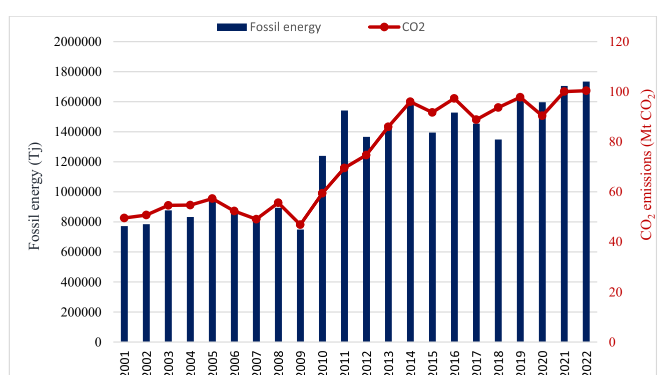

Fig. 3. Nigeria's fossil energy supplies (Tj) and CO_2 emissions (Mt CO_2) from fuel combustion.
Data sources: CO_2 emissions (IEA, n.d.-a); Fossil energy (Author's computation from IEA (n.d.-b) Data.

approximately 100 Mt. CO_2 in 2022. The trends of fossil energy supply and related CO_2 emissions appear to be broadly similar during the 2001–2022 time-frame. The high and increasing fossil energy supplies highlight the significance of oil, coal and gas as energy sources in different sectors of the Nigerian economy. Excessive dependence on fossil energies in Nigeria's energy segment has been ascribed to significant rise in CO_2 emissions, exceeding levels recorded in industrialized nations with entrenched low-carbon energies policies (Olujobi et al., 2023). The subdivisions of the transport sector are entirely reliant on fossil fuels, making it the largest consumer of fossil fuels (Akujor et al., 2022; Obada et al., 2024). The country therefore needs policy directives for gradual scaling of low-carbon energy adoption in key sectors, such as transportation, industries, and real estate. For example, transportation companies should be compelled to make a specified percentage of their fleets to use low-carbon energies, such as CNG. The bulk of Nigeria's electricity production is thermal and depends on fossil fuels which is highly carbon-emitting and breaches the Paris Agreement that Nigeria is a party to (Salakhetdinov & Agyyeno, 2020) with above 60 % of GHG emissions cuts expected in the energy sector (Roche et al., 2020). Nigeria significantly contributes to Africa's share of GHGs emission mainly from energy consumption (Afinotan, 2022; Okedere & Oyelami, 2021). The country's reliance on fossil fuels and energy inefficiency hinders its net-zero emissions goal, requiring a transition to decarbonization (Nwachukwu et al., 2024).

In spite of the high and increasing CO_2 from fossil energy sources, Nigeria has continued to rely on oil, natural gas, and coal for economic growth and energy supply, making the country's climate responsiveness challenging. Yet, pursuit of reliable and affordable energy access remains a critical priority for the development of the country. Despite the country's aspiration for universal energy access by 2030 in line with SDG 7, while access rate generally stands at 62 %, it is even poorer in the rural areas with 30 % access (Isihak, 2023). Also, negligible improvement has been recorded coupled with substantial indications of uneven distribution of electricity across the Nigerian landscape as the southern areas, state headquarters and industrial foci more electrified (Alabi et al., 2023). The poor energy access often triggers reliance on backup generators with high carbon footprints (Amakom et al., 2022). For instance, above 80 % of small and medium enterprises in Nigeria depend on a fossil-powered generator for operations as a result of failure of grid-connected supply (Roy et al., 2023). Therefore, the need to balance energy development to support economic growth and at the same time align with international climate obligations remains a burning challenge. Amid global ET drive, Nigeria appears to be oil and gas revenue-trapped, with renewed commitment not only in resuscitating its moribund refineries, but also issuance of licenses to private investors. Thus, in addition to FG-owned refineries, the country now has the largest privately-owned refinery in Africa as well as modular refineries, with other private-owned ones in the pipeline. Furthermore, illegal artisanal crude oil refining is prevalent, especially in the jungles of the Niger Delta (Bebeteidoh et al., 2020). Emissions from petroleum refining pose significant environmental threats, including hazards on the surroundings (Odekanle et al., 2021), including carbon from the artisanal crude oil refineries which have been found to breach environmental guidelines and permissible limits (Onakpohor et al., 2020). While licensed and standard refineries are not emission-proofed, they are relatively more operationally efficient and monitorable unlike artisanal refineries with no compliance to standard production guidelines coupled with illegal status. Fossil-fuel-based energy sources that emit GHGs are required to give way to cleaner, RE alternatives (Obada et al., 2024).

RE deployment in Nigeria

Promoting a green economy is crucial for mitigating CC risks (Fu et al., 2024; Han & Gao, 2024). Thus, deployment of REs is widely recognized as a significant pathway for transitioning from fossil fuels, providing opportunity for GHGs reduction and energy security (Adedokun et al., 2025). RE sources, such as biomass, hydro, wind, solar and hydrothermal systems, are essentially carbon-neutral, producing negligible GHG emissions (Elum & Momodu, 2017). Therefore, transitioning to RE to aid CC mitigation is an outstanding strategy that requires sustainability to attain energy need of posterity (Owusu & Asumadu-Sarkodie, 2018). The genre of hydro, wind, biomass and solar have been classified as the most important RE resources in Nigeria (Esan et al., 2019), with a capacity of 1562.5 MW (Bhuiyan et al., 2022).

Nigeria is endowed with vast low-carbon energy assets which are yet to be fully harnessed (Obada et al., 2024; Olujobi et al., 2023). For instance, although the country has the potential for generating over 18 GW from hydro assets, only 20 % of it has been harnessed for electrical energy generation (Esan et al., 2019). While rivers Niger and Benue, which are the two main rivers traversing the country, have a combined energy potential of 14,750 MW (Chanchangi et al., 2022), exploitation of small hydro-energy resources which are spread across Nigeria has been identified as a potential for tackling the energy consumption gap (Ugwu et al., 2022). Part of the country's generated hydroelectricity is supplied to its bordering nations such as Niger based on treaty (Ibrahim et al., 2021) despite lingering domestic energy shortfall.

Nigeria has initiated policies toward GHG emission reduction, particularly in the energy sector. CAT (2022) outlined such policy developments as including, "Sectoral Action Plans for Nigeria's NDC to the UNFCCC of 2017, Revised National CC Policy (2021), Nigeria's First Nationally Determined Contribution (2021 Update), National Renewable Energy and Energy Efficiency Policy (NREEEP) (2015), Electricity Vision: 30-30-30, CC Act (2021), Flare Gas (Prevention of Waste and Pollution) Regulations (S.I. No. 9 of 2018) and Regulations on Feed-In Tariff for R Energy sourced electricity in Nigeria (2015)." Also significant to the country's emission reduction drive is Nigeria ET Plan (ETP) of 2023, which aims to achieve a 65 % reduction in emissions, eradicate energy poverty, stimulate investment, and enhance energy efficiency (Nwachukwu et al., 2024). Significantly, the CC Act 2021 provides a framework for the attainment of the country's CC targets, including framework for the realization of net zero by 2050 whereas NREEEP focusses on RE development while also promoting EE.

Despite Nigeria's climate-related energy policies, studies have identified significant gaps, including vague provisions, poor coordination and misalignment, which hinder effective implementation and harmonization. For instance, while Adedokun et al. (2025) argue that policies supporting RE deployment are hindered by inadequate institutional coordination and policy misalignment, Nwankwo et al. (2024) contend that the country's energy policy lacks specific provisions for the development and deployment of biogas, hindering its potential to support climate objectives and expand energy access. Furthermore, Okoh and Okpanachi (2023) opine that institutional inaction and harmonization challenges act as obstacles within the energy structure while conflicting policy preferences and political-economic permutations trigger additional predisposition toward the overriding petroleum and gas driven economy. Thus, although Nigeria has set ambitious RE targets, policy implementation has stalled their realization, with missed short-term and mid-term targets (Adedokun et al., 2025). Olujobi et al. (2023) therefore emphasized creating workable policy structure as a critical option for unlocking Nigeria's renewable and carbon-neutral energy assets.

Fig. 4 shows the renewable electricity generation and renewable percentage from 2001 to 2022. Renewable electricity generation dipped from 8165 GWh in 2012 to 5315 GWh in 2013 before rising to 9397 GWh in 2022. The renewable percentage of electricity generation in the country declined from 39.50 % in 2001 to 17.44 % in 2015 before following a somewhat increasing and fluctuating pattern till 2022, with 2022 having 24.74 % renewable. Despite Nigeria's erratic Nigeria's electricity generation coupled with frequent national grid collapse, the removal of fuel subsidy could trigger adoption of RE sources.

The position of Nigeria among some Africa Countries in the Global ET Index Ranking (GETIR) for 2024 is presented in Fig. 5. The country

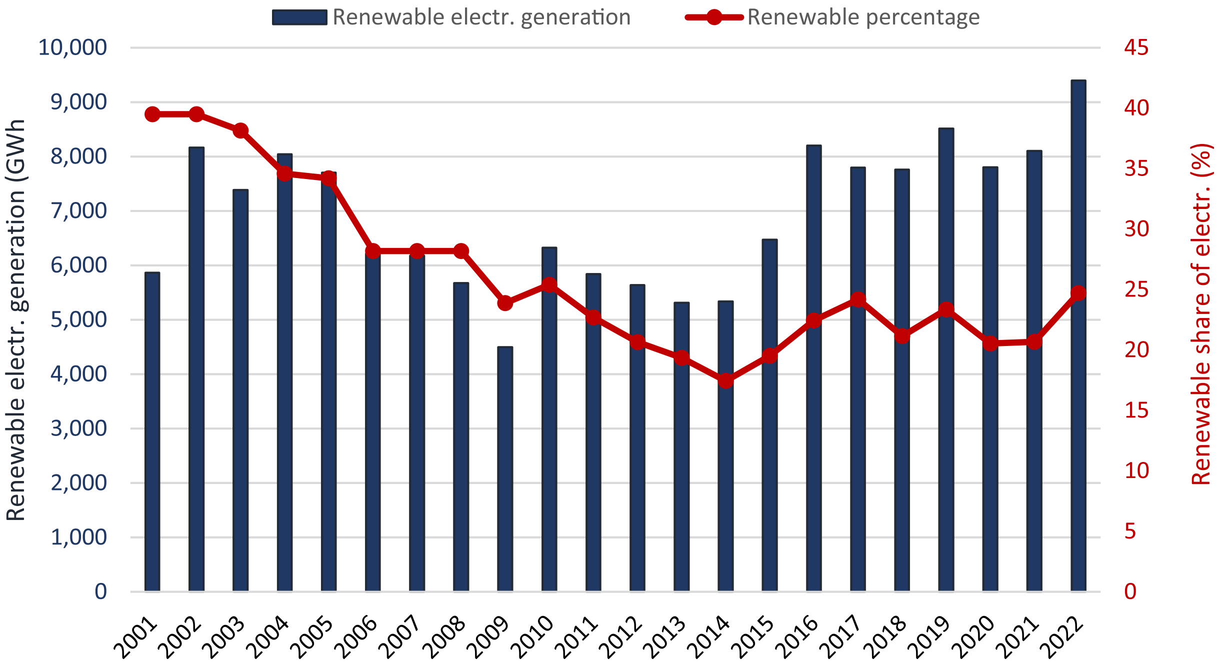

Fig. 4. Renewable electricity generation and renewable share of percentage of electricity.
Data source: CountryEconomy.com.

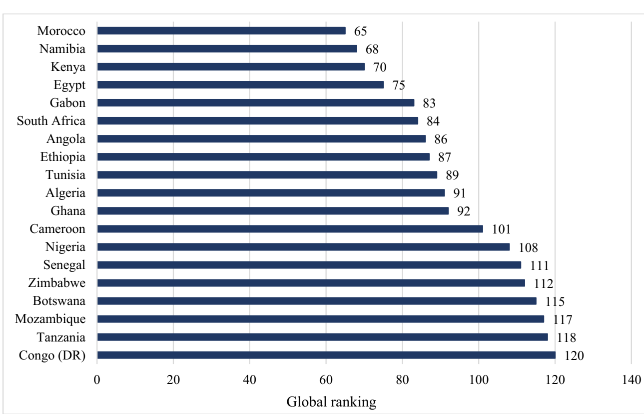

Fig. 5. Global ET Index Ranking 2024: The position of Nigeria and some Africa Countries.
Data source: Sasu (2024).

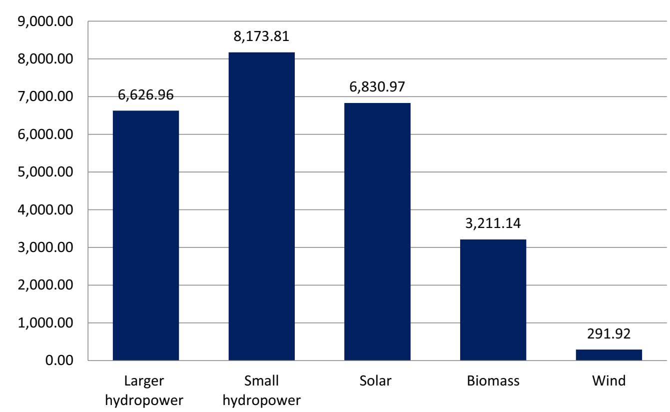

Fig. 6. Summary of long-term RE electricity targets (MW).
Data source: NREEEP Data (Federal Government of Nigeria, 2015).

ranked 108 globally and fell below smaller African economies such as Ghana, Tunisia, Angola, Gabon, Kenya and Morocco. The poor GETIR of Nigeria highlights the fact that its numerous CC commitment in the energy sector have not fully yielded the desired result. There is the need to translate policies into tangible CC goals through enhanced RE generation.

Fig. 6 shows Nigeria's ambitious electricity generation targets from different RE sources by 2030. The targets show that the country is expected to generate 25,143.80 MW of electricity from RE sources by 2030. Unfortunately, while Nigeria's energy demand is on the increase due to population growth, the huge RE resources across the geopolitical regions remain mostly unharnessed (Ajayi et al., 2022; Ugwu et al., 2022). Thus, less than six years to the 2030 SDG deadline, the country's energy supply from the RE sources remain far below the 2030 targets. Nigeria's electricity sector has however witnessed some developmental strides in recent years, including the enactment of the Electricity Act 2023, commissioning of the 240 MW Afam Three Fast Power and 50 MW Maiduguri Emergency Thermal Power plants as well as the 700 MW Zungeru hydropower plant coupled with new projects underway, such as 1900 MW Egbin Power expansion and the 1300 MW Gwagwalada Independent Power Plant (IEA, 2024). Overall, the country's energy development strategies exhibit conflicting climate realities: low-carbon goals while also prioritizing fossil energy expansion.

Techno-financial challenges of low-carbon ET

Notwithstanding the substantial environmental and economic advantages of low-carbon energy, particularly RE, significant technological and financial hurdles persist in Nigeria, impeding large-scale and widespread adoption. This section therefore critically examines the technological and financial barriers constraining low-carbon energy transition in the country.

Technological challenges

Although the low-carbon ET depends heavily on technology, Nigeria's technological limitations remain a significant barrier to its realization. This review identifies three main technological challenges to achieving a low-carbon ET in the country: infrastructural limitations, dearth of technological innovation, and inadequate skilled manpower (Table 2). Although Nigeria is rich in energy resources, its outdated electric infrastructure struggles to meet the soaring energy needs of its rapidly growing population, resulting in a significant energy supply-demand gap (Oyedepo et al., 2018). Developing countries (Nigeria inclusive) face the challenge of low grid network and EE (Babayomi et al., 2022). The production and transmission capacity of Nigeria and other African countries are abysmally inadequate coupled with obsolete and ineffective supply network (Adewuyi et al., 2020; Dioha et al., 2025). Prolonged technical ineffectiveness coupled with financial gaps have resulted in poor grid maintenance in Nigeria (Roy et al., 2023). Thus, Nigeria's power distribution suffers huge energy losses, resulting in only a small proportion of generated power getting to the end users (Adoghe et al., 2023). For instance, despite the country's 13 GW installed capacity, average available power generation capacity hovers around 4.5 GW due to deteriorating power infrastructure, which forces 40 % of electricity consumption to rely on backup generators (IEA, 2024).

Integrating RE into traditional grids poses a significant challenge, demanding improvements that ensures a reliable, green, and sustainable electricity supply (Adedokun et al., 2025; Kabeyi & Olanrewaju, 2023). However, despite policy efforts aimed at promoting a sustainable ET, RE technologies have remained not integrated into Nigeria's energy grid

Table 2
Technological threats to Nigeria's low-carbon ET.

S/N	Threat	Nature of threat	Source
1	Infrastructural limitations	Old grid infrastructure	Oyedepo et al. (2018); Adewuyi et al. (2020); IEA (2024); Dioha et al. (2025)
		Low grid network and EE	Babayomi et al. (2022)
		Energy losses	Adoghe et al. (2023)
		Vandalization of energy infrastructures	Adeyanju et al. (2020); Nwangwu et al. (2024); Adedokun et al. (2025)
		Poor grid maintenance	Roy et al. (2023)
		Inadequate generation and transmission capacity	Adewuyi et al. (2020); Dioha et al. (2025)
		Poor micro-grid adoption	Nwangwu et al. (2024)
2	Dearth of technological innovation	Lacks capacity for producing RE technology components	Adebayo et al. (2021); Obada et al. (2024); Abe and Azubuike (2024); Obada et al. (2024)
		Shortage of critical CC mitigation technologies	Nwachukwu et al. (2024); Nwali et al. (2024)
		Infancy of off-grid and on-grid technological adoption	Edomah et al. (2021)
		Dearth of innovative off-grid data collection	Ozoegwu and Akpan (2021)
		Fossil-reliant transport technology	Akujor et al. (2022); Obada et al. (2024)
		Reliance on imported technologies	Adebayo et al. (2021); Obada et al. (2024); Abe and Azubuike (2024)
		Poor incorporation of RE into the national grid	Kabeyi and Olanrewaju (2023); Adedokun et al. (2025)
		Energy inefficiencies	Babayomi et al. (2022); Adoghe et al. (2023)
		Emerging deployment of digital technologies	Nwaiwu (2021)
		Poor R&D	Adepoju et al. (2022)
3	Inadequate skilled manpower	Inadequate technical manpower	Obada et al. (2024)
		Reliance on expatriates for critical maintenance	Abe and Azubuike (2024)

(Adedokun et al., 2025), although decentralized RE solutions, including both off-grid and on-grid technologies, only began to emerge in Nigeria in the 2000s (Edomah et al., 2021). Furthermore, despite their potential to combat CC and alleviate electricity shortages, micro-grid adoption in Nigeria is hindered by concerns around security and management (Nwangwu et al., 2024). Several incidences of infrastructural damage due to the activities of insurgents and militants have been reported in different parts of Nigeria (Adedokun et al., 2025; Adeyanju et al., 2020; Nwangwu et al., 2024). The country also faces limited digitization and smart technology (Nwaiwu, 2021). Technology can enable the registration of off-grid power generation by providing digital platforms and mobile applications that streamline data collection, automate licensing processes, and improve real-time monitoring by regulatory authorities. However, uncertainty engulfs the installation capacity statistics of solar power in Nigeria which is complicated by dearth of nationwide registration of off-grid photovoltaic (PV) installation (Ozoegwu & Akpan, 2021). Furthermore, although blockchain technology has the potential to advance a sustainable energy landscape by enhancing energy-market effectiveness and transparency, facilitating the integration of RE resources, and promoting environmental monitoring and economic sustainability (Lv, 2023; Popkova et al., 2023), Nigeria as well as other countries in Africa are still at the emerging phase of utilization of digital technologies such as smart grids and blockchain in the energy division (Nwaiwu, 2021). Paucity of explicit evidence of application of blockchain in Nigeria's energy sector makes the ET to be hazy.

Nigeria lacks considerable capacity for producing RE technology gears, resulting in their importation (Abe & Azubuike, 2024; Adebayo et al., 2021; Obada et al., 2024). For instance, absence of local manufacturing of wind energy component parts has been identified as an obstacle to the penetration of wind energy (Adebayo et al., 2021). The country suffers shortage of critical climate change mitigation technologies (Nwachukwu et al., 2024). Notably, while the country relies heavily on fossil fuel-powered transport technology (Akujor et al., 2022; Obada et al., 2024), Carbon Capture, Use and Storage (CCUS) strategy which combines carbon capture and carbon storage (CSS) and carbon capture and utilization (CCU) technologies, is lacking, with development hindered, among others, inadequate policies, and limited public awareness (Nwali et al., 2024).

Although Nigeria's energy policy seeks to uphold administrative proficiency and local participation (Energy Commission of Nigeria, 2018), the country is still plagued by dearth of relevant manpower for the exploitation of climate-friendly energy options. Nigeria RE demands is hindered by a shortage of trained local technicians, emphasizing the need for enhanced technical skill transfer and training programmes, especially in rural areas (Obada et al., 2024). The requirement of annual maintenance visits by German experts for Nigeria's German-engineered machines highlights the need to move beyond technology transfer to technology absorption, guaranteeing that green technologies are adapted to local contexts and can be effectively deployed and maintained by local communities (Abe & Azubuike, 2024). Research and development (R&D) are cardinal to promoting development and improvement of existing energy technologies toward meeting the countries climate goals. Unfortunately, the country is plagued by dearth of research and development (R&D) on RE (Adepoju et al., 2022) coupled with mass exodus of skilled labour in search for greener pastures due to worsening hardship.

Financial barriers

This section examines contexts of financial barriers to low-carbon ET in Nigeria, as outlined in Table 3. Funding deficiency has been identified as a major obstacle in tackling the world's most critical environmental issues (Brand et al., 2021), particularly in Africa. With tripled external debts since 2008, making the largest debt increase and debt-to-revenue ration in the developing world, sub-Saharan Africa requires innovative financing solutions to access affordable capital and achieve its development and climate objectives (Gallagher et al., 2024). Specific

Table 3
Financial barriers to low-carbon ET.

S/N	Barrier	Nature of barrier	Sources
1	Debt	Mounting debt burden	Debt Management Office Nigeria (2025)
2	Policy implementation	Poor fiscal policy implementation	Adebayo et al. (2021); Isah et al. (2023)
3	Investment	Skewed fossil fuel investment priorities	Obada et al. (2024)
		Lack of investment guarantee	Adeyanju et al. (2020); Obada et al. (2024)
		Perceived high-risk of RE investments	Obada et al. (2024)
		Underinvestment (e.g., in ICT)	Chipangamate and Nwaila (2024); Abdukarim
4	Funding challenge and financial leakage	Weak home-driven funding mechanisms	Isah et al. (2023)
		Revenue deficit and corruption in the power sector	Roy et al. (2023)
		Poorly harnessed funding opportunities	Mutarindwa et al. (2024)
		Low awareness of carbon offset initiatives	Mohammad et al. (2023)
5	Cost	High initial cost of low-carbon technologies	FGN (2021b); Ogbonna et al. (2023); Obada et al. (2024); Adeyanju et al. (2020); Nyarko et al. (2023); Adedokun et al. (2025)
		High cost of importing RE technology components	Obada et al. (2024)

reference to Nigeria indicates that while RE development requires significant investment, the country needs $177 billion to achieve its Nationally Determined Contributions (NDC) by 2030 (FGN, 2021b), the country's total public debt as at 31st December 2024 stood at 94.2251 billion US dollars (Debt Management Office Nigeria, 2025). Increasing debt servicing burden coupled with budget deficits, have continued to threaten the realization of the country's climate goals, including its NDC through energy ET. Yet, the country's electricity sector has continued to suffer revenue deficits coupled with corruption, triggering wide regime financial rescues (Roy et al., 2023).

There are diverse instances of how investment limitation obstructs Nigeria's low-carbon ET. While green investment facilitates a seamless transition to a low-carbon economy (Gao et al., 2023), Africa's renewable drives are adversely affected by prevailing financial operations (Sweerts et al., 2019). Policy plays a critical role in influencing the scale of investment in RE technology (Abbass et al., 2022). Although policy suggestions such as tariff incentives, capital awards and Feed-in Tariffs (FiT) to boost solar power infiltration in Nigeria have been proposed, implementation is still partial (Adebayo et al., 2021). Nigeria's RE investment is hindered by vague policy and frail funding mechanisms (Isah et al., 2023). While Brazil's transition to RE is propelled by radical funding through its Development Bank, international organizations and multilateral development financial institutions constitute the chief funder of RE in Nigeria (Isah et al., 2023). Although Nigeria's is endowed with huge RE resources, representing viable market for participation of the private sector in its electricity sector, lack of investment guarantee remains a challenge (Adeyanju et al., 2020), foreign sources of funding could be unreliable due to unpredictability of global diplomatic relations.

A major challenge that hinders adoption of low-carbon energy is the high cost of associated technologies, particularly high initial cost (Obada et al., 2024; Ogbonna et al., 2023), including the cost of photovoltaic panels and batteries, wind turbines, and installations. Notably, while electric vehicles offer the greatest cost savings, reducing costs by up to 75 % per kilometer, and minimizing energy loss to 33 %, they are also associated with battery-related cost challenges (Farghali et al., 2023). Unfortunately, although Dimnwobi et al. (2022) have demonstrated that Nigeria's transition to RE is aided by the growth of the financial industry, Obada et al. (2024) have noted that financial institutions often view RE investments as high-risk, preferring to fund established fossil fuel projects, and consequently charge higher interest rates and offer shorter loan terms for RE initiatives. RE investors are confronted by price elasticity and production uncertainty risks, particularly for technologies extremely reliant on weather circumstances, like wind and solar (Alcorta et al., 2024) while utilization is considerably affected by financial risk (Li et al., 2025). Yet, the devalued state of the Nigerian currency makes importation of RE technological components highly expensive and unaffordable to majority of the people who live in poverty.

Underinvestment in Information and Communication Technology (ICT) in emerging markets hinders the advancement of RE transition, ultimately slowing progress (Chipangamate & Nwaila, 2024). There is low awareness of carbon offset initiatives (Mohammad et al., 2023) amid largely untapped funding opportunities (Mutarindwa et al., 2024). Despite the benefits of Environmental Impact Bonds (EIBs), they are largely unknown outside of conservation finance circles and project stakeholders, limiting their broader adoption and potential impact (Brand et al., 2021). While a survey of road users in northeastern Nigeria shows their willingness to pay for carbon offset at a low price, education and awareness are still necessary to promote environmental sustainability through carbon offset initiatives (Mohammad et al., 2023).

Despite the potential of Environmental, Social, and Governance (ESG) bonds to fund African governments' and corporations' CC mitigation efforts, the continent receives less than 0.3 % of global ESG bond issuance volume (Mutarindwa et al., 2024), which mirrors the prevailing under-utilization of low-carbon energy funding resources in Nigeria. Green finance (GF) has been shown to play a vital role in mitigating environmental degradation while simultaneously promoting sustainable economic growth of members of the Belt and Road Initiative (BRI) (Chin et al., 2024). While studies have established that GF facilitates RE advancement (Khan et al., 2024; Subramaniam & Loganathan, 2023; Tufail et al., 2024), green energy projects face significant challenges, including limited financing, low returns, high risks, and inadequate market capacity (Taghizadeh-Hesary & Yoshino, 2020). Key GF metrics which have a positive impact on investments in RE include depth, stability, and efficiency (Xia et al., 2023). Despite these array of funding opportunities, like many other developing economies, Nigeria is trapped in a cycle of underinvestment (Abdulkarim, 2023).

Technological low-carbon energy pathways

Grid modernization and decentralization

Developing infrastructure can substantially enhance energy access, reliability, and efficiency, especially in remote and disadvantage areas (Abe & Azubuike, 2024). Nigeria needs to carry out extensive grid maintenance and replacement of unserviceable components to reduce power loss during transmission. Moreover, transitioning to sustainable energy systems requires advanced technologies, including smart grid (Kabeyi & Olanrewaju, 2023) and integration of renewables. Additionally, developing micro-grids and mini-grids is necessary to serve rural and off-grid areas with RE. Off-grid strategies, comprising mini-grid and detached solutions could be relevant in unpowered rural areas (Gungah et al., 2019; Oyedepo et al., 2018). To this end, it is important to encourage distributed generation through rooftop solar, wind, and biomass systems.

Promotion of EE development

Accomplishing the 1.5 °C temperature goal requires enormous amounts of EE and climate-friendly technologies (Okoh & Okpanachi, 2023). Applying RE, EE technologies, smart design strategies can reduce energy consumption by up to 40 % (Farghali et al., 2023). While Nigeria is making strides, with the current initiative to convert vehicles to compressed natural gas (CNG) which could reduce vehicular CO_2 emissions, there is the need to increase conversion centres across the country. Furthermore. Achieving net-zero emissions in key sectors like cement production demand significant investments in EE (Roche, 2023), while deploying deep neutral network (DNN) in buildings can significantly reduce energy consumption (Farghali et al., 2023). To promote EE initiatives in Nigeria, sustainable energy development requires management systems, storage solutions (Kabeyi & Olanrewaju, 2023), and carbon offset programmes (Okoh & Okpanachi, 2023), which can capture CO_2 from power plants and industrial processes, and storing it underground (Nwali et al., 2024). To curb energy wastage, Nigeria needs to promote the use of EE appliances through providing tax holidays to local manufacturers and import duty waiver for importers of high energy efficient appliances. To this end, the country needs policy to make it compulsory for firms to submit energy audit report yearly, with appropriate sanction imposed on violators of energy-efficient practice.

Complementary deployment of REs

To overcome the limitations of intermittency associated with hydro, solar, and wind energy, RE sources should be deployed to complement each other, thereby bridging shortages caused by natural factors. For instance, hydropower can be effectively utilized in several regions to offset the seasonal fluctuations of irregular RE sources, such as solar (Gonzalez et al., 2022). As the country transition to net-zero emissions, natural gas is expected to play a bridging role in the short-term and medium-term, while solar may dominate the long-term technology mix (Shari et al., 2024). Furthermore, the Nigeria's vast and natural ecosystems offer a convenient and cost-effective pathway to mitigate CC through nature-based solutions (Ogbonna et al., 2023), such as ethanol from cassava, sugar cane, and jatropha feedstock and palm oil-based biodiesel. Since, waste management in Nigeria is currently inadequate, resulting in environmental pollution (Okere et al., 2019), the country's ecological diversity, enormous population size, and municipal and industrial wastes offer significant bio-fuel prospects (Nwozor et al., 2021), with a technical power prospect of approximately 2.33 EJ that could be generated from existing biomass resources (Jekayinfa et al., 2020).

Promotion of local manufacturing and technological absorption

To forester a smooth low-carbon ET, the Nigerian government should facilitate technology transfer partnerships between local firms and global clean-tech companies. To enable absorption of transferred technology, favourable local environment should be created to encourage adoption. This should include supporting domestic manufacturing of RE technologies, such as solar panels, wind turbines, and battery technologies through tax breaks and subsidies.

Advancing research, innovation, development

Because the low-carbon ET has both short-term and long-term goals, it is important that the country stays on track in deepening low-carbon energy research and promoting innovative approaches across all facets of the transition, supported by built-in monitoring and evaluation mechanisms. Knowledge dissemination is essential for a secure and equitable ET, which can help alleviate energy poverty and social disparities (Buonomano et al., 2023). Therefore, achieving robust low-carbon energy research should include promotion of strategic university-industry partnerships. While innovative technologies are critical to realizing energy efficiency and mitigate the impact of CC (Farghali et al., 2023), such innovative low-carbon technologies should encompass power generation and distribution, EE, and carbon capture and storage. For example, bioremediation and phytoremediation have been identified as effective low-carbon solutions for cleaning up the Niger Delta region, offering a cost-effective and adaptable approach to local environmental conditions (Azuazu et al., 2023).

Capacity building and development

To address shortfall in RE engineers and technicians, Nigeria needs to launch and encourage more technical training programmes. For instance, intensification of certification programmes for energy professionals could be vital to guarantee quality and safety in renewable installations. Moreover, existing university-based energy centres across Nigeria's geopolitical regions should be made to live up to their mandates by spearheading low-carbon energy innovation and deployment, thereby evolving into dynamic hatcheries of clean energy solutions.

Financial pathways to low-carbon energy

Adopting innovative and sustainable financing models

Adopting innovative and sustainable low-carbon energy financing strategies is critical to Nigeria's climate responsiveness. This could facilitate economic growth while balancing environmental safety and economic resilience (Hossin et al., 2024). Viable approaches include incentivizing private sector investment in RE (Obada et al., 2024), collective financing models where communities pool resources (Nduka, 2022), and blended finance, combining public and private funding (Isah et al., 2023). Thus, to enhance green investment, solutions include leveraging public institutions, pension funds, and insurance companies, while also implementing tax incentives, green credit guarantees, community trust funds, and risk-reduction strategies (Taghizadeh-Hesary & Yoshino, 2020). Community RE initiatives encompass community-owned, cooperative, public private partnerships (PPPs), and third-party ownership models (Kaze et al., 2025). PPPs are appropriate because of their capacity for risk management and cost effectiveness benefits, offering a flexible approach, enabling balanced risk and return distribution between public and private sectors (Tahir et al., 2024). They have been found to successful drive RE in countries like China and India (Raghutla & Kolati, 2023). Similarly, Egyptian RE projects are typically implemented as PPPs to leverage private sector financing and mitigate the government's burden of high upfront costs (Othman & Kallaf, 2023). This aligns with Nigeria's CC Act which broadens emission responsibilities to both government institutions and private sector partnerships (PPPs) to unlock financing and expand market opportunities for RE project developers (Nduka, 2022). Also, multinationals, especially in the oil sector, should channel their corporate responsibilities to host communities by establishing multipurpose RE projects instead of prevailing limited-purpose RE projects.

Green bonds, an eco-friendly investment instrument, have gained popularity since the Paris Agreement, offering traditional bond characteristics while funding environment projects (Gao et al., 2023). Since companies that issue green bonds tend to have better environmental performance, lower carbon emissions (García et al., 2023), it can be implemented as cost-effective options to enhance RE growth and mitigate CC (Akrofi et al., 2022; Rosoulinezhad & Taghizadeh-Hesary, 2022). Additionally, EIBs can be explored as mechanisms for generating capital required for environmental projects, repaying investors with interest from financial benefits generated by the project's environmental outcomes (Brand et al., 2021; Trotta, 2024).

Promoting cost reduction strategies

To reduce the adverse impacts of high exchange rate and high import duties on RE components, it is imperative to stabilize the value of the Naira and remove import duties on clean energy equipment to make renewable technology more affordable and adoptable. Rather than adopt outright ban of importation of solar panels, as it is being contemplated by the government, in the interim, local manufacturers should be protected from unfavourable competition from their foreign counterparts through incentives like tax holidays or tolerable tax, since their present production capacity cannot meet the high local demands due to the country's high and growing population size. Providing low-interest rates and tax incentives to solar low-carbon investors, among others, is important for achieving a low-carbon future in Nigeria (Shari et al., 2023). These measures coupled with appropriate regulatory frameworks can promote transparency, accountability, and fair competition, fast-tracking the country's ET (Abe & Azubuike, 2024). While cost can also be reduced through promotion of bulk procurement initiatives, the Central Bank of Nigeria (CBN) should intensify provision of RE grants and initiate fiscal policies that prioritizes disbursement of low-interest rates loans for RE technologies. It is also important to prioritize RE projects in budgetary allocation (Adebayo et al., 2021) and formulation of policies that promote the introduction of financial incentives, such as awarding RE firms tax discounts to induce non-public investors into the segment (Adeyanju et al., 2020).

De-risking RE investments

To reduce volatility, Nigeria needs to create sovereign green energy fund to provide guarantees for projects and implement credit enhancement programmes to support small and medium enterprises (SMEs) in the RE sector. Since investors may only risk their capital in RE ventures if they are sure of making a profit (Christophers, 2022), it is also important to create energy insurance schemes to tackle the financial risks connected with project fiascos. Since funding terms and eliminating investment risk can contribute significantly to realizing carbon neutrality (Matthäus & Mehling, 2020), the country needs to develop funding terms that are low-carbon energy-investment-friendly. Again, this should include CBN using its fiscal control instruments to direct preferential lending rates for RE investors and expand financial inclusion initiatives (Dimnwobi et al., 2022). Promoting the participation of non-banking organizations, such as insurance firms, can also tackle financial constraints in long-term clean energy ventures (Taghizadeh-Hesary & Yoshino, 2020). Also, because easing financial limitations aids both climate justice due to increase in RE and inexpensive energy in emerging economies (Calcaterra et al., 2024), adoption of PPPs could also offer flexible financing approach, enabling a balanced distribution of risks and returns between public and sector via a mix of financial instruments (Tahir et al., 2024). Lastly, it is imperative to carefully study global trade relation, particularly unfolding US-tariff hikes and adopt informed policy response, particularly taking into cognizance importation of RE components.

Carbon pricing and subsidy reforms

The financing challenge in the country's low-carbon ET can also be assuaged by intensifying implementation of carbon tax and introduction of emission trading system while sustaining fossil fuel subsidy phase out to generate and redirect funds to clean energy projects and provision of incentives. Carbon tax encourages consumers to reduce carbon emissions by switching to environment-friendly alternatives, and promoting healthier choices (Nemavhidi & Jegede, 2023). It is therefore considered as a key measure to reduce GHG emissions and support the Paris Agreement's goal of limiting global temperature increase to below 2 °C (Fujimori et al., 2020; Yang, 2024). It has consequently been argued that implementing carbon taxes can deter pollution, generate revenue for environmental mitigation, and attract foreign direct investment, making it vital for African countries to expedite its adoption (Yiadom et al., 2024). Fortunately, evidence shows that investing carbon tax revenue for climate-related projects increases public acceptance, perceived fairness, and effectiveness of the tax (Maestre-Andres et al., 2021). Besides, lower-income households would face relatively lesser financial burdens from carbon pricing and would benefit more from cash transfers through improved infrastructure (Dorband et al., 2022).

Canvassing for debt forgiveness

Sub-Saharan Africa requires debt relief, among others, to mobilize finance and support the Paris Agreement and SDGs (Gallagher et al., 2024). This could reduce Nigeria's financial burden, enabling the country to embark on capital-intensive low-carbon energy projects, such as building more hydro-electric power plants, particularly in the humid southern region, and establishing solar farms, especially in the semi-arid northern part of the country.

Leveraging international climate finance

Foreign direct investment and regional financial organizations' support are critical for scaling up RE investment (Abbass et al., 2022; Ibrahiem & Hanafy, 2021; Mutezo & Mulepo, 2021). Therefore, Nigeria needs to make optimal use of the array of multilateral funds from international institutions, such as global environment fund (GEF), green climate fund (GCF), least develop countries fund (LDCF), and special CC fund (SCCF). The country should explore low-carbon projects funding opportunities in World Bank and African Development Bank (AfDB). Additionally, the country in collaboration with other countries with similar emission profile need to send delegation of experts to the Conferences of the Parties (COP) to canvass better and realistic compensation by high polluting countries, such as China and the United States of America.

Strengthening financial policy and regulatory frameworks

Nigeria's energy strategies have continued to send mixed signal, promoting RE while also prioritizing fossil fuels. The country's low-carbon ET is hindered by insufficient policies and centralized energy strategies, highlighting the necessity for a more inclusive, participator, and decentralized approach (Kaze et al., 2025). Since these challenges can hinder techno-financial advancement toward low-carbon ET, the country needs frameworks harmonization, promoting specificity, devolution of legislative responsibility and inclusivity, to be more climate-driven. Government needs to develop a framework that promotes adoption of FiTs to ensure fixed payments to RE producers for the amount of electricity they generate and feed into the national grid over a stipulated time. This guaranteed investment return could make the RE sector attractive, stimulate grid expansion, and further decentralize the energy sector. Already the decentralization of the Nigerian electricity sector into the GenCos, TranCos and DisCos, with assigned regulatory authorities has led to growth of its transmission infrastructure up to 10,000 km (Babatunde et al., 2023).

Conclusion

This paper reviewed Nigeria's climate responsiveness in the energy sector, focusing on energy-climate complexities, techno-financial challenges, and pathways to low-carbon ET. Selected materials, comprising journal articles, conference proceedings, government policies, federal government technical reports, technical report, and data sourced from databases were reviewed adopting narrative review approach, under five key thematic areas: fossil energy-CO_2 dynamics, RE deployment, technological challenges, and financial barriers as well as pathways to low-carbon ET. Findings reveal that Nigeria's climate responsiveness in the energy sector is marked by contradictory trajectories–promoting a low-carbon ET while simultaneously expanding fossil fuel development amid rising trend in CO_2 emissions. Despite setting ambitious RE targets, the country's ET continues to be constrained by technological and financial challenges. The technological challenges to low-carbon ET include old grid infrastructures, poor grid maintenance, inadequate generation and transmitting capacity, poor micro-grid adoption, shortage of critical CC mitigation technologies, reliance on imported technologies, poor integration of RE into national grid, poor R&D, and inadequate skilled manpower. Financial threats to low-carbon ET include mounting debt burden, poor fiscal policy implementation, fossil energy-skewed investment, lack of investment guarantee, perceived high-risk of RE investment, weak domestic-driven funding mechanisms, corruption, poor harnessing of funding opportunities, high initial cost of low-carbon technologies, and high cost of imported RE technology components. To effectively tackle the technological threats to the country's low-carbon ET, proposed pathways include grid modernization and decentralization, advancing research, innovation and development, promotion of energy efficient development, facilitation of local manufacturing and technological transfer, and capacity building and development, while financial strategies for low-carbon ET include adoption of innovative financing models, such as PPPs, cooperatives, and third-party ownerships, promotion of cost reduction strategies, de-risking RE investments, adoption of carbon pricing and subsidy reforms, canvassing for debt forgiveness, and leveraging international climate financing. Other viable options include policy measures aimed at further decentralizing electricity sector to stimulate expansion of the RE sector and safeguarding energy infrastructures, adoption of FiTs, and gradual scaling of low-carbon energy deployment in key sectors, such as transportation, industries, and real estate. To promote capital flow to the RE sector, the CBN should consider stimulating flow of low interest loans into the sector using its fiscal control instruments while government should consider increase in budgetary allocation to RE projects. Overall, the study offers valuable insights into Nigeria's climate-responsiveness in the energy sector, highlighting energy-climate dynamics, the status of RE development, and key technological and financial challenges, while proposing viable pathways for advancing the low-carbon ET and enhancing energy access. Notwithstanding the breadth and insights of this review, reliance on a narrative rather than systematic approach may have introduced limitations, especially the risk of bias. While the review provides insights into Nigeria's climate responsiveness within the contexts of energy-climate complexities, techno-financial challenges, and pathways to low-carbon ET, further studies could explore perspectives such as quality control compliance of imported low-carbon energy technologies, justice and equity considerations and the role of sub-national governments in implementing climate-responsive energy policies.

CRediT authorship contribution statement

Godwin Oghenebrozie Atedhor: Writing – review & editing, Writing – original draft, Resources, Methodology, Conceptualization.

Declaration of competing interest

The author declares no conflict of interest.

References

Abbass, K., Qasim, M. Z., Song, H., Muntasir, M., Mahmood, H., & Younis, I. (2022). A review of the global climate change impacts, adaptation, and sustainable mitigation measures. *Environmental Science and Pollution Research, 29*, 42539–42559. https://doi.org/10.1007/s11356-022-19718-6

Abdulkarim, Y. (2023). A systematic review of investment indicators and economic growth in Nigeria. *Humanities and Social Sciences Communications, 10*, Article 500. https://doi.org/10.1057/s41599-023-02009-x

Abe, O., & Azubuike, V. (2024). (Re)examining the intersection between energy justice and energy transition in Africa. *Journal of Energy & Natural Resources Law, 42*(3), 279–299. https://doi.org/10.1080/02646811.2024.2356988

Abeydeera, L. H. U. W., Mesthrige, J. W., & Samarasinghalage, T. I. (2019). Global research on carbon emissions: a scientometric review. *Sustainability, 11*(14), 3972. https://doi.org/10.1016/10.3390/su11143972

Ackah, I., Opoku, F., & Anang, S. (2019). Switching on an environmentally friendly and affordable light in Africa: Evaluation of the role of natural gas. *Insight on Africa, 11*(1), 60–77. https://doi.org/10.1177/0975087818814932

Adebayo, H. B., Adio, S. A., & Oborien, B. O. (2021). Energy research in Nigeria: A bibliometric analysis. *Energy Strategy Reviews, 34*, Article 100629. https://doi.org/10.1016/j.esr.2021.100629

Adedokun, R., Strachan, P. A., Singh, A., & von Malmborg, F. (2025). Exploring the dynamics of socio-technical transitions: Advancing grid-connected wind and solar energy adoption in Nigeria. *Energy Research & Social Science, 119*, Article 103850. https://doi.org/10.1016/j.erss.2024.103850

Adepoju, O. O., David, L. O., & Nwulu, N. N. (2022). Analysing the impact of human capital on renewable energy penetration: a bibliometric review. *Sustainability, 14*(14), 8852. https://doi.org/10.3390/su14148852

Aderounmu, B., Azuh, D., Onanuga, O., Oluwatomisin, O., Ebenezer, B., & Azuh, A. (2021). Poverty drivers and Nigeria's development: implications for policy intervention. *Cogent Arts & Humanity, 8*, Article 1927495. https://doi.org/10.1080/23311983.2021.1927495

Adewuyi, O. B., Kiptoo, M. K., Afolayan, A. F., Amara, T., Alawode, O. I., & Senjyu, A. F. (2020). Challenges and prospects of Nigeria's sustainable energy transition with lessons from other countries' experiences. *Energy Reports, 6*, 993–1009. https://doi.org/10.1016/j.egyr.2020.04.022

Adeyanju, G. C., Osobajo, O. A., Otitoju, A., & Ajide, O. (2020). Exploring the potentials, barriers and option for support in the Nigeria renewable energy industry. *Discovery Sustainability, 1*(7). https://doi.org/10.1007/s43621-020-00008-5

Adoghe, A. U., Adeyemi-Kayode, T. M., Oguntosin, V., & Amahia, I. I. (2023). Performance evaluation of the prospects and challenges of effective power generation and distribution in Nigeria. *Heliyon, 9*, Article e14416. https://doi.org/10.1016/j.heliyon.2023.e14416

Afinotan, U. (2022). How serious is Nigeria about climate change mitigation through gas flaring regulation in the Niger Delta? *Environmental Law Review, 24*(4), 288–304. https://doi.org/10.1177/14614529221137142

Ajayi, O. O., Mokryani, G., & Edu, B. M. (2022). Sustainable energy for national climate change, food security and employment opportunities: implications for Nigeria. *Fuel Communications, 10*, Article 100045. https://doi.org/10.1016/j.jfueco.2021.100045

Akrofi, M. M., Okitasari, M., & Kandpal, R. (2022). Recent trends on the linkages between energy, SDGs and the Paris Agreement: a review of policy-based studies. *Discover Sustainability, 3*, Article 32. https://doi.org/10.1007/s43621-022-00100-y

Akujor, C. E., Uzowuru, E. E., Abubakar, S. S., & Amakom, C. M. (2022). Decarbonization of the transport sector in Nigeria. *Environmental Health Insights, 16*, 1–8. https://doi.org/10.1177/117863022211250

Alabi, O., Abubakar, A., Werkmeister, A., & Sule, S. D. (2023). Keeping the lights on or off: Tracking the progress of access to electricity for sustainable development in Nigeria. *Geojournal, 88*, 1535–1558. https://doi.org/10.1007/s10708-022-10689-2

Alcorta, P., Espinosa, M. P., & Pizarro-Irizar, C. (2024). Right and duty: Investment risk under different renewable energy support policies. *Environmental and Resource Economics, 87*, 3163–3204. https://doi.org/10.1007/s10640-024-00909-3

Amakom, C. M., Ogungbenro, O. A., Iheonu, N. O., Nkwoada, A., Iwueke, D. C., Anya, J., & Okoye, J. (2022). Annual carbon footprint from local electricity generation in Federal University of Technology, Owerri. *Environmental Health Insights, 16*, 1–6. https://doi.org/10.1177/11786302221136732

Arogundade, S., Hassan, A. S., & Mduduzi, B. (2024). Is climate change hindering the economic progress of Nigerian economy? *Heliyon, 10*, Article e39288. https://doi.org/10.1016/j.helyon.2024.e39288

Azuazu, I. N., Sam, K., Campo, P., & Coulon, F. (2023). Challenges and opportunities for low-carbon remediation in the Niger Delta: towards sustainable environmental management. *Science of the Total Environment, 900*, Article 165739. https://doi.org/10.1016/j.scitotenv.2023. 165739

Babatunde, O., Buraimoh, E., Tinuoye, O. M., Ayegbusi, C., Davidson, I., & Ghwavwe, D. E. (2023). Electricity sector assessment in Nigeria: the post-liberation era. *Cogent Engineering, 10*, Article 2157536. https://doi.org/10.10180/23311816.2022.2157536

Babayomi, O. O., Dahoro, D. A., & Zhang, Z. (2022). Affordable clean energy transition in developing countries: pathways and technologies. *IScience, 25*(5), Article 104178. https://doi.org/10.1016/j.isci.2022.104178

Bebeteidoh, O. L., Kometa, S., Pazouki, K., & Norman, R. (2020). Sustained impact of the activities of local crude oil refineries on the host communities. *Heliyon, 6*, Article e04000. https://doi.org/10.1016/j.heliyon.2020.e04000

Bhuiyan, M. A., Zhang, Q., Khare, V., Mikhaylov, A., & Pinter, G. (2022). Renewable energy consumption and economic growth nexus – a systematic review. *Frontiers in Environmental Science.*. https://doi.org/10.3389/fenvs.2022.878394

Brand, M. W., Seipp, K. Q., Saksa, P., Ulibarri, N., Bomblies, A., Mandle, L., Allaire, M., Wing, O., la Parker, E. A., May, J., Sanders, B. F., Rosowsky, D., Lee, J., Johnson, K., Gudino-Elizondo, N., Ajami, N., Wobbrock, N., Adriaens, P., Grant, S. B., … Gibbons, J. P. (2021). Environmental impact bonds: a common framework and looking ahead. *Environmental Research Infrastructure and Sustainability, 1*, Article 023001. https://doi.org/10.1088/2634-4505/ac0b2c

Buonomano, A., Baronea, G., & Forzano, C. (2023). Latest advancements and challenges of technologies and methods for accelerating the sustainable energy transition. *Energy Reports, 9*, 3343–3355. https://doi.org/10.1016/j.egyr.2023.02.015

Calcaterra, M., Reis, A., Fragkos, P., Briera, T., de Boer, H. S., Egli, F., Emmerling, J., Iyer, S., Polzin, F. H. J., Sanders, M. W. J. L., Schmidt, T. S., Serebriakova, A., Steffen, B., van de Ven, D. J., van Vuuren, D. P., Waidelich, P., & Tavoni, M. (2024). Reducing the cost of capital to finance energy transition in developing countries. *Nature Energy, 9*, 1241–1251. https://doi.org/10.1038/s41560-024-01606-7

CAT. (2022). Climate governance: Assessment of the government's ability and readiness to transform Nigeria into a zero emission society. Nigeria: CAT Climate Governance Series . February 2022. Available at https://climateactiontracker.og/documents/1014/2022_02_CAT_Governance_Report_Nigeria.pdf Accessed on January 24, 2025.

Chanchangi, Y. N., Adu, F., Ghosh, A., Sundaram, S., & Mallick, T. K. (2022). Nigeria's energy review: focusing on solar energy potential and penetration. *Environment, Development and Sustainability, 25*, 5755–5796. https://doi.org/10.1007/s10668-022-02308-4

Chaudhury, T., Kayani, U. N., Gul, A., Haider, S. A., & Ahmad, S. (2023). Carbon emission, environmental distortions, and impact on growth. *Energy Economics, 126*, Article 107040. https://doi.org/10.1016/j.eneco.2023.107040

Chin, M., Ong, S., Ooi, D. B., & Puah, C. (2024). The impact of green finance on environmental degradation in BRI region. *Environment, Development and Sustainability, 26*, 303–318. https://doi.org/10.1007/s10668-022-02709-5

Chipangamate, N. S., & Nwaila, G. T. (2024). Assessment of challenges and strategies for driving energy transitions in emerging markets: a socio-technological systems perspectives. *Energy Geoscience, 5*, Article 100257. https://doi.org/10.1016/j.engoes.2023.100257

Christophers, B. (2022). Fossilised capital: Price and profit in the energy transition. *New Political Economy, 27*(1), 146–159. https://doi.org/10.1080/13563467.2021.1926957

CountryEconomy.com (n.d.) Nigeria – Electricity Generation 2023. Available at: https://countryeconomy.com/energy-and-environment/electricity-generation/nigeria. Accessed March 29, 2025.

Dagnachew, A. G., Poblete-Cazenave, M., Pachauri, S., Holf, A. F., van Ruijven, B., & van Vuuren, D. P. (2020). Integrating energy access, efficiency and renewable energy policies in sub-Saharan Africa: a model-based analysis. *Environmental Research Letters, 15*, Article 125010. https://doi.org/10.1088/1748-9326/abcbb9

Debt Management Office Nigeria. (2025). *Nigeria's Total Public Debt as at December 31, 2024*. Federal Ministry of Finance. Available at: https://www.dmo.gov.ng/debt-profile/total-public-debt/5215-total-public-debt-as-at-december-31-2024 Accessed April, 19, 2025.

Dimnwobi, S. K., Madichie, C. V., Ekesiobi, C., & Asongu, S. A. (2022). Financial development and renewable energy consumption in Nigeria. *Renewable Energy, 192*, 668–677. https://doi.org/10.1016/j.renene.2022.04.150

Dioha, M. O., Abraham-Dukuma, M. C., & Dato, P. (2025). Unearthing the reality of 'Zombie energy systems in Africa's energy transition. *Environmental Research Energy, 2*, Article 01300. https://doi.org/10.1088/2753-3751/ada77d

Dioha, M. O., Emodi, N. V., & Dioha, E. C. (2019). Pathways for low carbon Nigeria in 2050 by using NECAL2050. *Renewable Energy Focus*. https://doi.org/10.1016/j.ref.2019.02.004

Dodo, U. A., Ashigwuike, E. C., & Eronu, E. M. (2021). Renewable energy readiness in Nigeria: a review focusing on power generation. *Uniabuja Journal of Engineering and Technology, 1*(1), 115–144.

Dorband, I., Jakob, M., Steckel, J. C., & Ward, H. (2022). Double progressivity of infrastructure financing through carbon pricing – Insights from Nigeria. *World Development Sustainability, 1*, Article 100011. https://doi.org/10.1016/j.wds.2022.100011

Edomah, N., Ndulue, G., & Lamaire, X. (2021). A review of stakeholders and interventions in Nigeria's electricity sector. *Heliyon, 7*, Article e07956. https://doi.org/10.1016/j.heliyon.2021.e07956

Elum, Z. A., & Momodu, A. S. (2017). Climate change mitigation and renewable energy for sustainable development in Nigeria. A discourse approach. *Renewable and Sustainable Energy Reviews, 76*, 72–80. https://doi.org/10.1016/j.rser.2017.03.040

Energy Commission of Nigeria. (2018). *National Energy Policy* (Draft Revised ed.). Abuja: Federal Ministry of Science and Technology.

Esan, O. C., Anthony, E. J., & Obaseki, O. S. (2019). Utilization of renewable energy for improved power generation in Nigeria. *Journal of Physics: Conference Series, 1299*, Article 012026. https://doi.org/10.1088/1742-6596/1299/1/012026

Farghali, M., Osman, A. I., Mohamed, I. M. A., Chen, Z., Chen, L., Ihara, I., Yap, P., & Rooney, D. W. (2023). Strategies to save energy in the context of the energy crisis: a review. *Environmental Chemistry Letters, 21*, 2003–2039. https://doi.org/10.1007/s10311-023-01591-5

Federal Government of Nigeria, FGN. (2015). *National Renewable Energy and Energy Efficiency Policy (NREEEP)*. Abuja: Ministry of Power.

FGN. (2021a). *Nigeria's first Nationally Determined Contribution – 2021 Update*. Abuja: Federal Ministry of Environment.

FGN. (2021b). *National Policy on climate Change*. Abuja: Federal Ministry of Environment.

Fu, C., Lu, L., & Pirabi, M. (2024). Advancing green finance: a review of climate change and decarbonization. *Digital Economy and Sustainable Development, 2*, 1. https://doi.org/10.1007/s44265-023-00026-x

Fujimori, S., Hasegawa, T., & Oshiro, K. (2020). An assessment of the potential of using carbon tax revenue to tackle poverty. *Environmental Research Letters, 15*, Article 114063. https://doi.org/10.1088/1748-9326/abb55d

Gallagher, K. P., Ramos, L., Were, A., & Marques, M. Z. (2024). Debt distress and climate-resilient development in sub-Saharan Africa. *Journal of African Economies, 33*(2), ii8–ii25. https://doi.org/10.1093/jae/ejae028

Gao, L., Guo, K., & Wei, X. (2023). Dynamic relationship between green bonds and major financial asset markets from the perspective of climate change. *Frontiers in Environmental Science, 10*, Article 1109796. https://doi.org/10.3389/fenvs.2022.1109796

García, C. J., Herrero, B., Mirrales-Quirós, J. L., & Mirrales-Quirós, M. D. (2023). Exploring the determinants of corporate green bond issuance and its environmental implication: the role of corporate board. *Technological Forecasting and Social Change, 189*, Article 122379. https://doi.org/10.1016/j.techfore.2023.122379

Ghazouani, A., Xia, W., Jebli, M. B., & Shahzad, U. (2020). Exploring the role of carbon taxation policies on CO2 emissions: contextual evidence from tax implementation and non-implementation European countries. *Sustainability, 12*, 8680. https://doi.org/10.3390/su12208680

Gonzalez, J. M., Tomlinson, J. E., Martínez, E. A., Ceseña, M., Basheer, J. M., Obuobie, E., … Harou, J. J. (2022). Designing diversified renewable energy systems to balance multisector performance. *Nature Sustainability.*. https://doi.org/10.1038/s41893-022-01033-0

Gungah, A., Emodi, N. V., & Dioha, M. O. (2019). Improving Nigeria's renewable energy policy design: a case study approach. *Energy Policy, 130*, 89–100. https://doi.org/10.1016/j.enpol.2019.03.059

Han, J., & Gao, H. (2024). Green finance, social inclusion, and sustainable growth in OECD member countries. *Humanity & Social Sciences Communications, 11*, 140. https://doi.org/10.1057/s441599-024-02662-w

Hossin, M. A., Alemzero, D., Abudu, H., Yin, S., Mu, L., & Panichakarn, B. (2024). Examining public private partnership investment in energy towards achieving sustainable development goal 7 for ASEAN region. *Scientific Reports, 14*, 16398. https://doi.org/10.1038/s41598-024-66800-9

Ibrahiem, D. M., & Hanafy, S. A. (2021). Do energy security and environmental quality contribute to renewable energy? The role of trade openness and energy use in North Africa countries. *Renewable Energy, 179*, 667–678. https://doi.org/10.1016/j.renene.2021.07.019

Ibrahim, I. D., Hamam, Y., Alayli, Y., Jamiru, T., Sadiku, E. R., Kupolati, W. K., Ndambuki, J. M., & Eze, A. A. (2021). A review on Africa energy supply through renewable energy production: Nigeria, Cameroon, Ghana and South Africa as a case study. *Energy Strategy Reviews, 38*, Article 100740. https://doi.org/10.1016/j.esr.2021.100740

IEA. (2024). Electricity 2024: analysis and forecasting to 2026. Available at https://managenergy.ec.europa.eu/publications/electricity-2024-analysis-and-forecast-2026_en?prefLang=da Accessed February 21, 2025.

IEA (n.d.) CO2 Emissions From Fuel Combustion, Nigeria. Available at: https://www.iea.org/countries/nigeria/emissions. Accessed: April 19, 2025.

IEA (n.d.) Evolution of Total Energy Supply in Nigeria Since 2000. Available at: https://www.iea.org/countries/nigeria/emissions. Accessed: April 19, 2025.

In, S. Y., Weyant, J. P., & Manav, B. (2022). Pricing climate-related risks of energy investments. *Renewable and Sustainable Energy Reviews, 154*, Article 111881. https://doi.org/10.1016/j.rser.2021.111881

IPCC. (2023). Summary for policymakers. In Core Writing Team, H. Lee, & J. Romero (Eds.), *Climate change 2023: Synthesis Report, Contribution of Working Group I, II, III to sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1–34). Geneva, Switzerland: IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647.001.

Isah, A., Dioha, M. O., Deberth, R., Abraham-Dukuma, M. C., & Butu, H. M. (2023). Financing renewable energy: policy insights from Brazil and Nigeria. *Energy, Sustainability and Society, 13*(2). https://doi.org/10.1186/s13705-022-00379-9

Isihak, S. R. (2023). Achieving universal electricity access in line with SDG7 using GIS-based Model: an application of OnSSET for rural electrification planning in Nigeria. *Energy Strategy Reviews, 45*, Article 101021. https://doi.org/10.1016/j.esr.2022.101021

Jekayinfa, S. O., Orisaleye, J. I., & Pecenka, R. (2020). An assessment of potential resources for biomass energy in Nigeria. *Resources, 9*, Article 92. https://doi.org/10.3390/resources9080092

Kabeyi, M. J. B., & Olanrewaju, O. A. (2023). Smart grid technologies in the sustainable energy transition: a review. *International Journal of Sustainable Energy, 42*(1), 685–758. https://doi.org/10.1080/14786451.2023.2222298

Kaze, K., Balta-Ozkan, N., & Shrimpton, E. (2025). Connecting power to people: Integrating community renewable energy and multi-level governance towards low-carbon energy transition in Nigeria. *Energy Research and Social Sciences, 121*, Article 103938. https://doi.org/10.1016/j.erss.2025.103938

Khan, S., Akbar, A., Nasim, I., Hedvičáková, & Bashir, F. (2024). Green finance development and environmental sustainability: a panel data analysis. *Frontiers in Environmental Science, 10*, Article 1039705. https://doi.org/10.3389/fenvs.2022.1039705

Kilinc-Ata, N., & Dolmatov, I. A. (2023). Which factors influence the decisions of renewable energy investors: Empirical evidence from OECD and BRICS countries. *Environmental Science and Pollution Research, 30*, 1720–1736. https://doi.org/10.1007/s11356-022-22274-8

Kumar, C. R., & Majid, M. A. (2020). Renewable for sustainable development in India: Current status, future prospects, challenges, employment, and investment opportunities. *Energy, Sustainability and Society, 10*(2). https://doi.org/10.1186/s13705-019-0232-1

Li, R., Wang, Q., & Sun, J. (2025). Financial risk and renewable energy: Exploring the influence of urbanization and natural resource rents across 112 countries. *Humanities & Social Sciences Communications, 12*, Article 170. https://doi.org/10.1057/s41599-025-04481-z

Lv, Y. (2023). Transitioning to sustainable energy: Opportunities, challenges, and the potential of blockchain technology. *Frontiers in Energy Research, 11*, Article 1258044. https://doi.org/10.3389/fenrg.2023.1258044

Maestre-Andres, S., Drews, S., Savin, I., & van den Bergh, J. (2021). Carbon tax acceptability with information provision and mixed revenue uses. *Nature Communications, 12*, 7017. https://doi.org/10.1038/s41467/-021-27380-8

Matthäus, D., & Mehling, M. (2020). De-risking renewable energy investments in developing countries: a multilateral guarantee mechanism. *Joule, 4*, 2627–2645. https://doi.org/10.1016/j.joul.202.10.011

Mohammad, S., Maji, I. K., Saari, M. Y., Salisu, L. N., & Dahiru, I. M. (2023). Analysis of willingness to pay for carbon emission reduction by road users in northeastern Nigeria. *Social Sciences & Humanity, 8*(1), Article 1006652. https://doi.org/10.1016/j.ssaho.2023.100652

Muktar, M., Adun, H., Cai, D., Obiora, S., Taiwo, M., Ni, T., Ozsahin, & Bamisile, O. (2023). Juxtaposing sub-Saharan Africa's energy poverty and renewable energy potential. *Scientific Reporting, 13*, 11643. https://doi.org/10.1038/s41598-023-38642-4

Mutarindwa, S., Schäfer, D., & Stephen, A. (2024). Certification against greenwashing in nascent bond markets: Lessons from ESG bonds. *Eurasian Economic Review, 14*, 149–173. https://doi.org/10.1007/s40822-023-00257-5

Mutezo, G., & Mulepo, J. (2021). A review of Africa's transition from fossil fuels to renewable energy using circular economy principles. *Renewable and Sustainable Energy Reviews., 137*, Article 110609. https://doi.org/10.1016/j.rser.2020.110609

Nduka, E. (2022). Reducing carbon footprint by replacing generators with solar PV systems: a contingent valuation study in Lagos, Nigeria. *Environment and Development Economics, 28*, 387–408. https://doi.org/10.1017/S1355770X22000316

Nemavhidi, M., & Jegede, A. O. (2023). Carbon tax as a climate intervention in South Africa: a potential aid or hindrance to human right. *Environmental Law Review, 25*(1), 11–27. https://doi.org/10.1177/14614529221149836

Noah, I. A. (2024). Nigeria's climate change act, conditional and unconditional nationally determined contributions, and the principles of common but differentiated responsibilities. *Law Review, 0*(0), 1–19. https://doi.org/10.1177/14614529241272183

Nsafon, B. E. K., Same, N. N., Yakub, A. O., Chaulagain, D., Kumar, N. M., & Huh, J. (2023). The justice and policy implications of clean energy transition in Africa. *Frontiers in Environmental Science, 11*, Article 1089391. https://doi.org/10.3389/fenvs.2023.1089391

Nwachukwu, C. O., Diemuodeke, E. O., Briggs, T. A., Ojapah, M. M., Okereke, C., Okedu, K. E., & Kalam, A. (2024). Low/zero technology diffusion and mapping for Nigeria's decarbonization. *International Journal of Sustainable Energy, 43*(1), Article 2317146. https://doi.org/10.1080/14786451.2024.2317146

Nwaiwu, F. (2021). Digitalisation and sustainable energy transitions in Africa: Assessing the impact of policy and regulatory environments on the energy sector in Nigeria and South Africa. *Energy, Sustainability and Society, 11*, 48. https://doi.org/10.1186/s13705.021-00325-1

Nwali, O. I., Oladunjoye, M. A., & Alao, O. A. (2024). A review of atmospheric carbon sequestration pathways; processes and current status in Nigeria. *Carbon Capture Science & Technology, 12*, Article 100208. https://doi.org/10.1016/j.ccst.2014.100208

Nwangwu, S., Abubakar, J. A., & Ademola, O. F. (2024). The impact of stand-alone systems in Nigeria's energy distribution sector and present-day challenges. *IOP Conference Series: Earth and Environmental Science, 1322*, Article 012010. https://doi.org/10.1088/1755-1315/1322/1/012010

Nwankwo, N. C., Madougou, S., Inoussa, M. M., Okonkwo, E., & Derkyi, N. S. A. (2024). Review of Nigeria's renewable energy policies with focus on biogas technology penetration and adoption. *Discover Energy, 4*, Article 14. https://doi.org/10.1007/s43937-024-00035-7

Nwozor, A., Owoye, G., Olowojolu, O., Ake, M., Adedire, S., & Ogundele, O. (2021). Nigeria's quest for alternative clean energy through biofuels: an assessment. *IOP Conference Series: Earth Environmental Science, 655*, Article 012054. https://doi.org/10.1088/1755-1315/655/1/012054

Nyarko, K., Whale, J., & Urmee, T. (2023). Drivers and challenges of off-grid renewable energy-based projects in West Africa: a review. *Heliyon, 9*, Article e16710. https://doi.org/10.1016/j.heliyon.2023.e16710

Obada, D. O., Muhammad, M., Tajiri, S. B., Kekung, M. O., Abolade, S. A. M., Akinpelu, S. A., & Akande, A. (2024). A review of renewable energy resources in Nigeria for climate change mitigation. *Case Studies in Chemical and Environmental Engineering, 9*, Article 100669. https://doi.org/10.1016/j.cscee.2024.100669

Odekanle, L., Bakut, C. B., Olalekan, A. P., Ogundokun, R. O., Aremu, C. O., Sonibare, J. A., … Fakinle, B. S. (2021). Assessment of the contribution of TEX air pollutant from Nigeria's petroleum refineries to the ambient air quality: part II. *Cogent Engineering, 8*(1), Article 1947007. https://doi.org/10.1080/23311916.2021.1947007

Ogbonna, C. G., Nwachi, C. C., Okeoma, I., & Fagbemi, O. A. (2023). Understanding Nigeria's pathway to carbon neutrality using the multilevel perspective. *Carbon Neutrality, 2*, 24. https://doi.org/10.1007/s43979-023-00065-5

Okedere, O. B., & Oyelami, S. (2021). Emission inventory of greenhouse gases and sustainable energy for mobile telecommunication facilities in Nigeria. *Environmental Challenges, 4*, Article 100203. https://doi.org/10.1016/j.envc.2021.100203

Okere, J. K., Ofodum, C. M., Azorji, J. N., & Nwosu, O. J. (2019). Waste-to-energy: a circular economy tool towards climate change mitigation in Imo State, South-Eastern, Nigeria. *Asian Journal of Advanced Research and Reports, 7*(1), 1–17. https://doi.org/10.9734/AJARRR/2019/v7i130164

Okoh, A. S., & Okpanachi, E. (2023). Transcending energy transition complexities in building a carbon-neutral economy: the case of Nigeria. *Cleaner Energy Systems, 6*, Article 100069. https://doi.org/10.1016/j.cles.2023.100069

Olujobi, O. J., Okorie, U. E., Olarinde, E. S., & Aina-Pelemo, A. D. (2023). Legal responses to energy security and sustainability in Nigeria's power sector amidst fossil fuel disruptions and low carbon energy distribution. *Heliyon, 9*, Article e17912. https://doi.org/10.1016/j.heliyon.2023.e17912

Onakpohor, A., Fakinle, B. S., Sonibare, J. A., Oke, M. A., & Akeredolu, F. A. (2020). Investigation of air emissions from artisanal petroleum refineries in the Niger-Delta Nigeria. *Heliyon, 6*, Article e05608. https://doi.org/10.1016/j.heliyon.2020.e05608

Othman, K., & Kallaf, R. (2023). Renewable energy public-private projects in Egypt: perceptions of the barriers and key success factors by sector. *Alexandria Engineering Journal, 75*, 513–530. https://doi.org/10.1016/j.aej.2023.06.009

Owusu, P. A., & Asumadu-Sarkodie, S. (2018). A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Engineering, 3*, Article 1167990. https://doi.org/10.1080/23311916.2016.1167990

Oyedepo, S. O., Babalola, O. P., Nwanya, S. C., Kilanko, O., Leramo, R. O., Aworunde, A. K., Adekeye, T., Oyebanji, J. A., Abidakun, A. O., & Agberegha, O. L. (2018). Towards a sustainable electricity supply in Nigeria: the role of decentralized renewable energy system. *European Journal of Sustainable Development Research, 2*(4), 40. https://doi.org/10.208797/ejosdr/3908

Ozoegwu, C. G., & Akpan, P. U. (2021). A review and appraisal of Nigeria's solar energy policy objectives and strategies against the backdrop of the renewable energy policy of the Economic Community of West African States. *Renewable and Sustainable Energy Reviews, 143*, Article 110887. https://doi.org/10.1016/j.rser.2021.110887

Popkova, E. G., Bogoviz, A. V., Lobova, S. V., Vovchenko, N. G., & Sergi, B. S. (2023). Blochain, sustainability and clean energy transition. *Global Transitions, 5*, 64–78. https://doi.org/10.1016/j.glt.2023.04.002

Raghutla, C., & Kolati, Y. (2023). Public-private partnerships investment in energy as new determinants of renewable energy. The role of political cooperation in China and India. *Energy Reports, 10*, 3092–3101. https://doi.org/10.1016/j.egyr.2023.09.139

Roche, M. Y. (2023). Built for net-zero: analysis of long-term greenhouse gas emissions pathways for the Nigerian cement sector. *Journal of Cleaner Production, 383*, Article 135446. https://doi.org/10.1016/j.clepro.2022.135446

Roche, M. Y., Verolme, H., Agbegbu, C., Binnington, T., Fishchedick, 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

Rosoulinezhad, E., & Taghizadeh-Hesary, F. (2022). Role of green finance in improving energy efficiency and renewable energy development. *Energy Efficiency, 15*, 14. https://doi.org/10.1007/s12053-022-10021-4

Roy, P., Watkins, M., Iwuamadi, C. K., & Ibrahim, J. (2023). Breaking the cycle of corruption in Nigeria's electricity sector: off-grid solutions for local enterprises. *Energy Research & Social Science, 101*, Article 103130. https://doi.org/10.1016/j.erss.2023.103130

Salakhetdinov, E., & Agyyeno, O. (2020). Achieving energy security in Africa: prospects of nuclear energy development in South Africa and Nigeria. *African Journal of Science, Technology, Innovation and Development*. https://doi.org/10.1080/20421338.2020.1799538

Sasu, D. D. (2024). *Energy Transition Index (ETI) Ranking of African Countries in 2024, by Position in Global Ranking.* Statista. https://www.statista.com/statistics/1250596/energy-transition-index-ranking-in-africa-byglobal-ranking (Accessed December 31, 2024).

Schneider, N. (2020). Population growth, electricity demand and environmental sustainability: Insights from a vector auto-regressive approach. *International Journal of Environmental Studies*. https://doi.org/10.1080/00207233.2021.1905317

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

Shari, B. E., Moumouni, Y., Ohunakin, O. S., Blechinger, P., Madougou, S., & Rabani, A. (2024). Exploring the role of green hydrogen for distributed energy access planning towards net-zero emissions in Nigeria. *Sustainable Energy Research, 11*, Article 16. https://doi.org/10.1186/s40807-024-00107-1

Subramaniam, Y., & Loganathan, N. (2023). Does green finance affect renewable energy development in Singapore. *Journal of Asian Business and Economic Studies, 31*(3), 162–174. https://doi.org/10.1108/JABES-02-2023-0052

Sweerts, B., Longa, F. D., & van der Zwaan, B. (2019). Financial de-risking to unluck Africa's renewable energy potential. *Renewable and Sustainable Energy Reviews, 102*, 75–82. https://doi.org/10.1016/j.rser.2018.11.039

Taghizadeh-Hesary, F., & Yoshino, N. (2020). Sustainable solutions for green financing in renewable energy project. *Energies, 13*, 788. https://doi.org/10.3390/en13040788

Tahir, J., Atkinson, M., Tian, Z., Kassem, M., Ahmad, R., & Martinez, P. (2024). A critical analysis of public private partnership model in energy from waste projects. *Sustainable Futures, 8*, Article 100240. https://doi.org/10.1016/j.sftr.2024.100240

The World Bank Group. (2023). The world by income. Available at: https://datatopics.worldbank.org/world-development-indicators/the-world-by-income-and-region.html Accessed December 5, 2023.

Tomala, J., Mierzejewski, M., Urbaniec, M., & Martinez, S. (2021). Towards sustainable energy development in sub-Saharan Africa: challenges and opportunities. *Energies, 14*, Article 6037. https://doi.org/10.3390/en14196037

Trotta, A. (2024). Environmental impact bonds: review, challenges, and perspectives. *Current Opinion in Environmental Sustainability, 66*, Article 101396. https://doi.org/10.1016/j.cosust.2023.101396

Tufail, M., Song, L., & Khan, Z. (2024). Green finance and green growth nexus: evaluating the role of globalization and human capita. *Journal of Applied Economics, 27*(1), Article 2309437. https://doi.org/10.1080/15140326.2024.2309437

Tunde, O. L., Adewole, O. O., Alobid, M., Szucs, I., & Kassouri, Y. (2022). Analysis of CO2 emissions data i Nigeria using a modified Mann-Kendal and change point detection approaches. *Energies, 15*(3), 766. https://doi.org/10.3390/en15030766

Ugwu, C. O., Ozor, P. A., & Mbohwa, C. (2022). Small hydropower as a source of clean and local energy in Nigeria: prospects and challenges. *Fuel Communications, 10*, Article 100046. https://doi.org/10.1016/j.jfueco.2021.100046

Wenga, T., Chinyama, S. R., Gwenzi, W., & Jamro, I. A. (2023). Quantification of bio-wastes availability for bioenergy production in Zimbabwe. *Scientific African, 20*, Article e01634. https://doi.org/10.1016/j.sciaf.2023. e01634

Worldometer. (2025). Nigeria Population (Live). Available at: https://www.worldometers.infor/world-population/nigeria-population/ Accessed April 21, 2025.

Xia, L., Liu, Y., & Yang, X. (2023). The response of finance toward the sustainable environment: The role of renewable energy development and institutional quality. *Environmental Science and Pollution Research, 30*, 59249–59261. https://doi.org/10.1007/s11356-023-26430-6

Yadzi, S. K., & Dariani, A. G. (2019). CO2 emissions, urbanization and economic growth: evidence from Asian countries. *Economic Research-Ekonomska Istrazivanja, 32*(1), 510–530. https://doi.org/10.1080/1331677x.2018.1556107

Yang, L. (2024). Research on the collaborative pollution reduction effect of carbon tax policies. *Sustainability, 16*, Article 935. https://doi.org/10.3390/su16020935

Yiadom, E. B., Mensah, L., Bokpin, G. A., & Mawutor, J. K. M. (2024). Carbon tax adoption and foreign direct investment: evidence from Africa. *Cogent Economics & Finance, 12*(1), Article 2312783. https://doi.org/10.1080/23322039.2024.2312783

Yusuf, A. M., Abubakar, A. B., & Mamman, S. O. (2020). Relationship between greenhouse gas emission, energy consumption, and economic growth: Evidence from some selected oil-producing African countries. *Environmental Science and Pollution Research, 27*, 15815–15823. https://doi.org/10.1007/s11356-020-08065-z