RSC Sustainability

CRITICAL REVIEW

View Article Online
View Journal | View Issue

Check for updates

Cite this: *RSC Sustainability*, 2025, **3**, 2534

Unlocking renewable energy materials in Nigeria: availability, application, and roadmap for sustainability

Ekele Dinneya-Onuoha *

Received 20th February 2025
Accepted 2nd May 2025

DOI: 10.1039/d5su00121h

rsc.li/rscsus

Nigeria's energy landscape remains highly dependent on fossil fuels, with approximately 60% of the population lacking consistent electricity access. Renewable energy (RE) offers a pathway to enhanced energy security, economic growth, and reduced carbon emissions. Although Nigeria has significant RE potential—ranging from solar (5.5 kW h per m^2 per day) to wind and biomass—these resources remain underutilized due to infrastructure, financial, and policy challenges. Solar photovoltaic (PV) technology, while promising, faces high costs due to import dependencies, as does battery storage technology reliant on lithium-ion cells. Additionally, materials for wind and biomass energy production are constrained by limited local manufacturing. Addressing these issues through material innovation and local sourcing is critical; ongoing research in Nigeria explores bio-based materials and sustainable practices, while government programs, though nascent, are beginning to promote local manufacturing. Local initiatives demonstrate potential for RE development, as evidenced by small-scale solar and biomass projects utilizing indigenous resources. However, financial constraints, supply chain challenges, and limited Research and Development (R&D) hinder progress. Moving forward, Nigeria must invest in policy reform and incentive programs to attract private investment in RE and reduce import costs for critical materials. Expanding R&D in material science, fostering partnerships between local researchers and international organizations, and providing targeted training in RE technology and material science are essential. With a unified focus on building a sustainable energy framework, Nigeria can harness its abundant resources for a more resilient and independent energy future.

Sustainability spotlight

This study advances sustainability by addressing Nigeria's renewable energy (RE) material challenges, promoting local material production, and reducing reliance on fossil fuels. By evaluating key RE materials—such as silicon for photovoltaics, bio-based energy storage, and lightweight composites for wind turbines—this research supports the development of a self-sustaining RE industry. The findings align with the UN Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 13 (Climate Action). Enhancing Nigeria's RE material supply chain fosters energy security, reduces carbon emissions, and drives economic growth, making the nation less vulnerable to global energy price fluctuations while supporting long-term environmental sustainability and industrial development.

1 Introduction

The rapid expansion of the global population, combined with the demands of modern industry and lifestyle, has created a significant gap in the supply of energy.[1] Meeting this gap requires a substantial and immediate increase in clean, stable, and reliable energy sources.[2–4] The ongoing reliance on depleting fossil fuels to meet energy needs not only strains the environment but also poses serious risks to public health.[5] For many developing nations, including those in sub-Saharan Africa, stable and dependable energy remains out of reach, hampering economic and social progress.[5,6] Energy access is essential to economic development, societal growth, agricultural productivity, and the improvement of living standards. According to several studies, approximately 1.2 billion people worldwide still lack access to stable, modern energy sources, with nearly half of this population living in sub-Saharan Africa.[7–10] In Nigeria, the region's most populous country, an estimated 100 million people are without reliable, clean energy,[11–13] a situation that underscores the nation's pressing energy poverty.

Driven by mounting concerns about climate change and global warming, the world has witnessed an unprecedented acceleration in the deployment of RE technologies. By the end of 2023, the global installed capacity of renewables—including

Department of Pure and Industrial Chemistry, University of Nigeria, Nsukka Postal Code 410001, Nigeria. E-mail: ekele.onuoha@unn.edu.ng

solar, wind, hydropower, geothermal, marine, and bioenergy—had reached approximately 4448 GW, marking a 15% increase over the previous year (see Fig. 1).[14] This rapid growth reflects a widespread transition toward cleaner and more sustainable energy systems.[15,16] The global RE market is projected to maintain this momentum, growing at a compound annual growth rate (CAGR) of 4.22% in the coming years.[15] Notably, China and the United States are leading the global solar PV market with installed capacities of approximately 760 GW and 265 GW, respectively.[17] In Africa, the total installed RE capacity is estimated at 62 GW, primarily concentrated in hydropower, solar PV, and biomass projects.[18] These global trends highlight both the urgency and the opportunity for developing nations like Nigeria to capitalize on renewable technologies and align with global sustainability goals.

Nigeria's struggle with energy poverty is especially pressing given its abundant potential for RE sources, including solar, hydroelectric, and wind resources. Geographically positioned to harness the sun's power, Nigeria experiences solar radiation levels that average approximately 5.5 kW h per m^2 per day with the northern part of the country receiving significantly higher levels at approximately 7 kW h m^2 per day, one of the highest rates on the African continent.[19] This level of solar exposure represents a powerful opportunity to generate substantial electricity if effectively harnessed, enough to significantly reduce Nigeria's dependence on fossil fuels and address the chronic energy shortage affecting its population.[20–22] Similarly, Nigeria's extensive rivers and water bodies present a significant opportunity for hydropower development, with an estimated potential of around 14.120 GW across the country.[23] Currently, however, only about 2.1 GW of this potential is being harnessed, leaving a vast 12.02 GW underutilized.[24] This unexploited capacity, according to Nchege and Okpalaoka,[23] could be pivotal in supplying consistent energy to remote communities, powering agricultural production, supporting irrigation systems, and providing essential services in rural areas. For instance, small-scale hydropower projects on rivers in rural regions could deliver affordable, off-grid power solutions to communities that lack reliable access to the national grid, significantly enhancing local economic activities and improving quality of life. As much of Nigeria's population is engaged in agriculture, harnessing even a fraction of the untapped hydropower potential could play a transformative role in rural economic development, stabilizing food production and contributing to Nigeria's overall energy security.[25–27]

Additionally, wind energy, especially in Nigeria's northern regions, presents a valuable addition to the country's RE portfolio.[28] Northern Nigeria has wind speeds averaging between 5.0 to 6.5 m s^{-1} at a height of 10 meters, with even higher speeds recorded in some locations during the dry season.[29–31] This is sufficient to support small to medium-scale wind power installations. The International Renewable Energy Agency (IRENA) estimates that Nigeria's wind energy potential is at 3200 MW.[32] However, the country's RE Roadmap pegs this estimate to exceed 4000 MW with the consideration of variables such as the varying wind speeds across the country's different

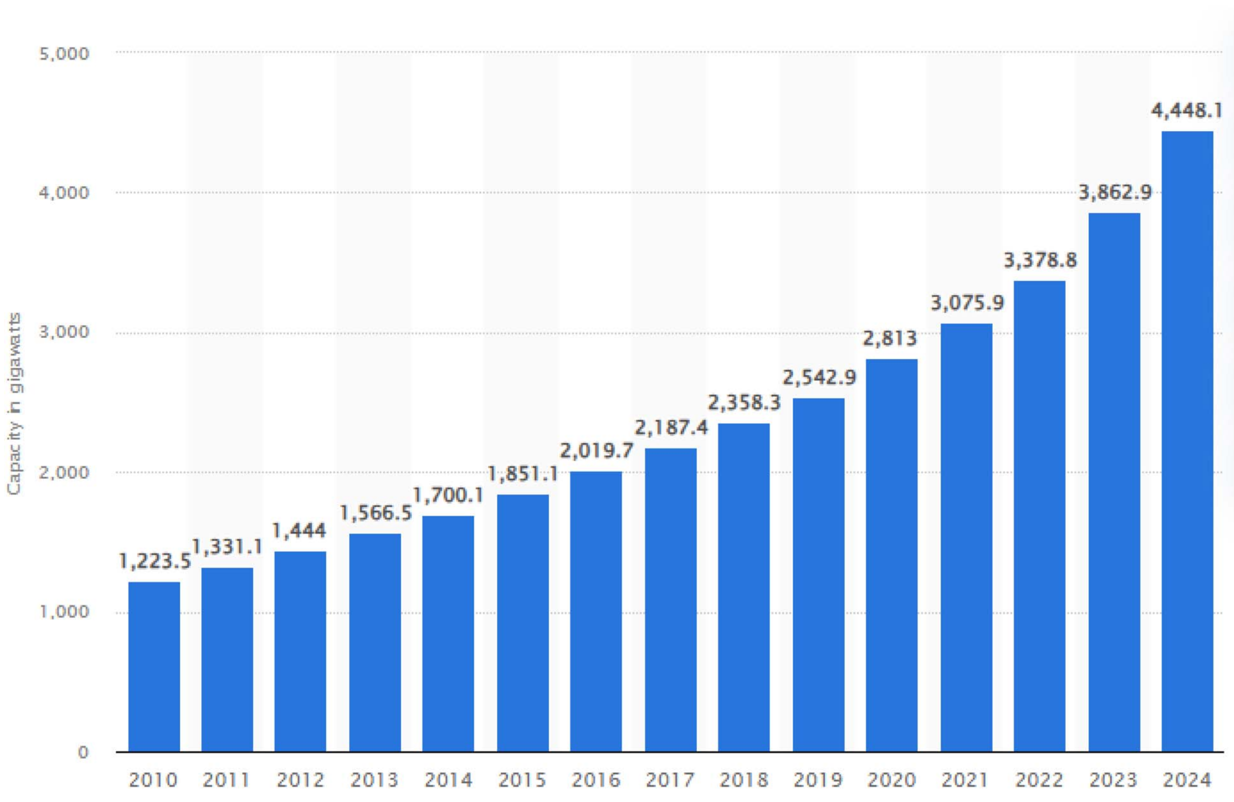

Fig. 1 Cumulative RE capacity worldwide from 2010 to 2024.[14]

regions. Wind farms strategically placed in northern regions could serve as a reliable supplementary source during the dry season, offsetting potential declines in solar and hydropower output and stabilizing energy availability throughout the year.[33,34] With targeted investment, this untapped resource could not only diversify Nigeria's energy mix but also provide sustainable power to rural areas and help reduce the national grid's dependency on fossil fuels.[31]

Localizing material production for RE technologies could be transformative for Nigeria, reducing reliance on costly imports and fostering economic resilience. In other emerging economies, the production of bio-based energy storage, recycled materials, and other locally sourced components has driven both sustainability and affordability in RE.[35–37] This work examines Nigeria's existing capacity to produce materials for RE technologies and identifies the critical gaps that, if addressed, could facilitate the country's transition toward sustainable energy. By analyzing Nigeria's available resources, current challenges, and opportunities for material innovation, this study provides valuable insights into how domestic material production could increase RE adoption, drive energy security, and foster economic growth in Nigeria.

2 Analytical frameworks

2.1 Energy transition

Energy Transition Theory (ETT) provides a conceptual lens for understanding the shift from conventional fossil fuel-based energy systems to more sustainable, RE solutions.[38] ETT is typically applied in contexts where economies shift from one dominant energy source to another, as seen in Europe's transition from coal to natural gas and renewables.[38,39] Nigeria, however, presents a unique case. Despite the longstanding use of RE, the country remains heavily dependent on fossil fuels, particularly crude oil and natural gas, which account for over 80% of energy consumption.[40,41] The transition narrative in Nigeria is therefore not one of complete substitution but of diversification and optimization. A critical application of ETT in Nigeria must consider the 'lock-in' effect of fossil fuel dependency, which refers to the structural, political, and economic entrenchment of oil and gas in the national energy mix. According to Barazza and Strachan,[42] energy transitions are non-linear and path-dependent, meaning that even with the presence of RE sources, systemic barriers—such as infrastructural deficits, regulatory inertia, and market failures—may delay or distort the transition process.

A crucial component of ETT is the socio-technical systems approach, which posits that energy transitions require the interplay of technological advancements, policy frameworks, economic incentives, and social acceptance.[43] In Nigeria, RE materials such as lithium, silicon, and bio-based materials for solar panels, batteries, and biofuels are gaining traction.[41,44–47] However, the lack of a fully integrated value chain for these materials limits their contribution to large-scale RE deployment. Furthermore, the absence of a robust energy governance framework exacerbates the slow pace of transition. While Nigeria's Renewable Energy Master Plan (REMP) and the Energy Transition Plan (ETP) provide blueprints for achieving cleaner energy targets,[48,49] the implementation gap remains significant. The socio-technical perspective within ETT highlights that energy transitions are not merely technological shifts but require institutional coordination, capacity building, and market readiness, areas where Nigeria continues to struggle.

The Multi-Level Perspective (MLP), a sub-framework within ETT, categorizes energy transitions into three levels: the niche level (emerging innovations), the regime level (dominant energy systems), and the landscape level (macro-environmental influences such as global energy policies and climate change concerns).[50] In Nigeria's case:

• Niche innovations: Nigeria has witnessed emerging RE projects, particularly in solar PV, wind, and biomass energy. The rise of decentralized energy solutions, such as mini-grids and solar home systems, signals an effort to circumvent the weak national grid.[51] However, these initiatives often remain isolated, underfunded, or donor-dependent, failing to displace fossil fuel reliance.[51,52]

• Regime challenges: Nigeria's energy regime remains dominated by oil and gas, with fossil fuel subsidies distorting market incentives for renewables.[40,41,53] Unlike European transitions where policy reforms drive systemic change, Nigeria's regulatory landscape is marked by inconsistency and weak enforcement.[19,54] While ETT and sustainability transitions suggest that regimes adapt when pressures from landscapes and niches align, Nigeria's regime displays a resilience to change, as political elites benefit from oil rents, stalling meaningful transitions.[55]

• Landscape pressures: global climate agreements, international investment trends, and grassroots activism exert pressure on Nigeria's energy landscape.[56] However, Nigeria's response has been fragmented. Climate policies such as the REMP exist but lack robust implementation mechanisms, further complicating transition efforts.[57]

Although ETT provides valuable insights, its traditional application assumes a linear trajectory from fossil fuels to renewables, which does not fully capture Nigeria's energy complexity. Instead, Nigeria's experience aligns more with a 'hybrid transition model' where RE coexists with conventional sources rather than replacing them entirely. This calls for a reconceptualization of ETT to accommodate energy diversification strategies rather than strict transitions. Moreover, the theory's emphasis on technological and economic shifts often overlooks socio-political realities, particularly in developing economies like Nigeria where policy inconsistency, infrastructural deficits, and governance challenges shape the energy landscape. A more context-sensitive adaptation of ETT would integrate these elements to provide a realistic roadmap for Nigeria's energy future.

3 Renewable energy resources in Nigeria

Nigeria's RE resources present an estimated potential capacity of over 136 000 MW, distributed across all regions of the

Table 1 Nigeria's RE resources – estimated reserves and production

Resource	Reserves	Production	References
Hydropower (large scale)	14.12 GW	2.1 GW	24 and 62
Hydropower (small scale <30 MW)	3.5 GW	0.06058 GW	62
Wave and tidal energy	150 000 TJ/16.6 × 10^6 tonnes per year	—	58
Fuel wood	21.63 million hectares	66.21 million m^3	63
Animal waste	245 million assorted animals	17.69 million tonnes per year	64 and 65
Municipal waste	4.51 million tonnes per year	—	64
Energy crops and agricultural residues	72 million hectares of arable land	0.256 million tonnes per day	58
Solar energy	3.5–7.0 kW h per m^2 per day	6 MW h per day (solar PV)	58
Wind energy	2–4 m s^{-1} at 10 m height	—	31

country.[58] However, the utilization rate of these resources remains low, primarily due to limited government investment in promoting widespread adoption and development of RE. For Nigeria to achieve sustainable socioeconomic growth and development without exacerbating climate change, it is crucial to enhance the effective deployment of these RE resources.[58–60] According to recent findings, the estimated RE reserves in Nigeria demonstrate a potential that is approximately 1.5 times greater than that of fossil fuels.[58,61] Hydropower has historically been the dominant source of electricity generation and distribution in the country (see Table 1).[23,66,67] The following sections provide a detailed analysis of the four primary RE resources available in Nigeria.

3.1 Wind energy

Nigeria holds significant potential for wind energy across various regions, with wind conditions comparable to those harnessed internationally for RE.[29,31,68] Wind energy offers diverse applications to meet the country's energy demands, such as water pumping for domestic and irrigation purposes, agricultural processing, and eventually electricity generation. Obada *et al.*[58] posit that harnessing wind energy for these uses could notably reduce dependence on fossil fuel-based electricity. The average annual wind speed ranges from approximately 2.0 m s^{-1} along the coast to about 9.5 m s^{-1} in northern areas. Wind power densities, measured perpendicular to the wind direction, varies between 3.4 W m^{-2} in coastal regions and 520 kW m^{-2} in the far north, with an air density of 1.1 kg m^{-3}.[69,70]

Analysis indicates that northern and central states—such as Sokoto, Katsina, Jigawa, Yobe, Kano, Bauchi, Kaduna, Nasarawa, and Plateau—exhibit favorable wind characteristics, suitable for large-scale wind energy production.[58] However, wind energy currently contributes minimally to Nigeria's energy mix.[58] In a preliminary effort to evaluate Nigeria's wind resource potential, the Ministry of Science and Technology conducted a wind mapping study, concluding that while Nigeria falls within a low to moderate wind regime, there is still potential for localized energy generation.[58,71]

Despite limitations, notable projects include a planned 100 MW wind farm in Plateau State and a 10 MW project in Katsina.[72] Aliyu *et al.*[73] noted that a small 5 kW wind electricity conversion system has been installed for village electrification in Sayya Gidan Gada, Sokoto State, alongside other standalone systems primarily used for water pumping (1 kW systems in Kedada and Goronyo in Bauchi and Katsina States, respectively).[74] The Katsina wind farm project, the country's first of its scale, was initiated in 2010 with a projected completion date of 2012. However, by 2016, only five of the planned 37 turbines had been installed, reflecting challenges in project execution and development.[58]

Recent studies have undertaken the categorization of Nigeria's wind profiles to assess RE potential across various regions. Ajayi *et al.*[75] conducted a comprehensive evaluation of wind power potential at ten locations within the southwestern states of Lagos, Oyo, Osun, Ondo, and Ekiti. Using 10-meter wind speed data from the Nigerian Meteorological Agency spanning 24 years (1987–2010), the research identified these areas as viable for wind energy generation. The findings indicate average wind speeds from 1.9 to 5.3 m s^{-1}, with potential speeds reaching 6.2 m s^{-1}, particularly in Lagos and Oyo, which show strong promise for large-scale wind power projects. For effective deployment across all sites, the study recommends low-speed turbines with cut-in speeds between 2–3 m s^{-1} and rated speeds (VR) of 10–12 m s^{-1}.

Ohunakin[76] confirmed substantial wind energy potential in Nigeria's northeastern zone at five meteorological stations—Potiskum, Nguru, Bauchi, Yola, and Maiduguri. This study used 10-meter wind speed data from 1971 to 2007, extrapolated to 50 meters using the power law, to determine suitability for extensive wind energy research. Key sites, including Potiskum, Maiduguri, and Bauchi, displayed monthly wind speeds ranging from 3.92 to 7.04 m s^{-1} and power densities from 53.82 to 299.88 W m^{-2}, highlighting these locations as prime candidates for wind energy projects.

Despite Nigeria's considerable wind energy potential—particularly in the northern regions such as Sokoto, Katsina, and Jos—its exploitation remains minimal due to a range of structural, technical, economic, and institutional challenges. One of the most prominent obstacles is the lack of reliable and comprehensive wind resource data, which impedes effective site selection and investment planning. According to Ohunakin,[76] although wind speeds in parts of northern Nigeria have been reported to range between 3.5 and 7.0 m s^{-1} at a height of 10 meters, these values are generally insufficient to support utility-scale wind power generation.[77,78] The absence of long-term meteorological data and modern resource mapping further discourages private sector participation. A notable example highlighting this challenge is the Katsina Wind Farm Project, initiated in 2005 with the aim of generating 10 MW of power.[72] Despite being one of Nigeria's flagship wind projects, it faced chronic delays due to poor feasibility assessments, mismanagement, and insecurity in the region. As documented by Ajayi *et al.*,[75] technical faults and logistical issues plagued the project, and it remained largely non-operational for over a decade. Even though some progress was later made in test-running turbines, the project has yet to operate at full capacity. This situation underscores a broader problem of poor project execution and insufficient institutional coordination in the RE sector.

Another critical barrier is infrastructure inadequacy, particularly in terms of transmission networks and grid connectivity. Most areas with viable wind resources are located far from Nigeria's aging and overstretched national grid, making integration technically challenging and financially unattractive. Majid[79] argues that without significant investment in grid expansion and modernization, utility-scale wind energy projects will continue to face grid evacuation constraints. Moreover, the cost of establishing off-grid wind systems is often prohibitive without adequate subsidies or financial incentives.[77] Policy inconsistency and weak regulatory enforcement further exacerbate the situation. While national frameworks such as the National Renewable Energy and Energy Efficiency Policy (NREEP, 2015) mention wind energy as a priority area, there is a glaring absence of specific incentives, feed-in tariffs, or fiscal mechanisms tailored to wind power development.[80] This policy vacuum deters foreign investors and local entrepreneurs alike.

Moreover, technical capacity and public awareness remain low, which impairs the development of indigenous solutions and limits the pool of qualified personnel to design, install, and maintain wind systems. Training institutions and universities in Nigeria rarely focus on wind technology in their RE curricula, contributing to over-reliance on foreign expertise. As Adetokun and Muriithi[81] observe, capacity-building initiatives must accompany technical investments to ensure sustainability and foster local innovation. Insecurity in key wind-prone regions—particularly in the North—also presents a serious deterrent. The Katsina wind project, for instance, suffered work stoppages due to insurgent activity, which not only delayed progress but also endangered workers and discouraged further investment.[72] In such environments, even donor-funded or government-supported projects face overwhelming operational risks.

While Nigeria holds appreciable wind energy potential, actual development is hindered by a combination of technical deficiencies, infrastructural gaps, policy and regulatory weaknesses, insufficient financing models, and socio-political instability. Without a coordinated and strategic response that addresses these interlinked barriers—particularly through robust policy support, improved data collection, and institutional reforms—the expansion of wind energy in Nigeria is unlikely to achieve scale or sustainability.

3.2 Biomass resources

Biomass encompasses waste products from plants, animals, households, and businesses that can be converted into usable energy, including forest plants and residues, production waste, municipal trash, animal waste, and agricultural crops and residues.[82–84] This RE source is considered one of the world's most abundant and sustainable.[85] Plants grow daily through photosynthesis, utilizing sunlight, while animals consume plant materials, creating a consistent supply of biomass energy that is estimated to be about five times the world's current energy needs. Despite its potential, global biomass use remains inefficient. Reports suggest that biomass accounts for roughly 14% of global energy, with developing countries—especially rural areas—contributing about 38% of this consumption.[86–90]

In Nigeria, biomass resources are crucial for sustainable rural electrification due to their availability in many regions. The country's biomass has an estimated annual energy potential of 2.58 billion GJ.[64] Annually, over 43.4 billion kilograms of fuelwood are used for domestic heating and other purposes.[58] According to Oyeniran and Isola,[91] charcoal and firewood remain the primary cooking fuels for most low-income urban and rural residents, though outdated stoves, with efficiencies below 10%, lead to substantial energy wastage and can sometimes result in biomass scarcity. Modern, efficient stoves could potentially increase conversion efficiency to over 20%, thereby reducing biomass usage and mitigating the adverse effects of burning biomass, such as excessive smoke and particulate matter-related air pollution.[58,92,93]

Bioenergy technology for electricity generation in Nigeria can be advanced through various biomass conversion methods, including direct combustion in improved stoves, gasification with biomass gasifiers, pyrolysis, and other thermochemical and biochemical techniques.[91] These technologies support applications in grid electricity, distributed generation, and standalone systems.[64] Many Nigerian states are actively promoting the cultivation of oil seeds necessary for biofuel production.[94] Key biomass resources in Nigeria include crops, forage grasses, shrubs, animal waste, forestry residues, agricultural and municipal waste, industrial by-products, and aquatic biomass.

High-potential crops such as sugarcane, sweet sorghum, and maize are readily available for biofuel production.[95] Nigeria currently encourages the cultivation of oil seeds and energy crops for biofuel, which could serve as a renewable alternative to fossil fuels, especially for small-scale enterprises.[96] Additionally, biogas production through anaerobic digestion of plant-derived biomass is another promising approach. Potential biogas sources include cassava peels and leaves, sewage, aquatic plants, algae, cow and poultry manure, among other waste materials.[97–99] With approximately 227 500 tons of fresh animal waste produced daily, Nigeria could generate an estimated 6.8 million m^3 of biogas, assuming 0.03 m^3 of biogas per kilogram of fresh animal dung.[100] Recent research in Nigeria has focused on improving biogas production and developing advanced biogas burners for both rural and urban use. Okoro *et al.*[101] reviewed 161 scientific publications from 2010 to 2021, highlighting the potential of agri-residues such as cassava and palm waste for bioenergy production. The research emphasized the importance of understanding agri-residue aggregation, technological advancements, and socio-economic factors to unlock the full potential of modern bioenergy in Nigeria. Hosseini and Wahid[102] investigated energy production from palm oil mill effluent (POME) biogas, finding that ultra-lean POME biogas could generate 10.8 MW of power, with a 0.7 MW increase when 2% hydrogen was added. Other studies by Aisien and Aisien,[103] Odekanle *et al.*,[104] and Jekayinfa and Scholz[105] demonstrated that co-digestion of different feedstocks can improve biogas yield and quality, supporting both household and industrial energy supply.

Several projects have showcased the feasibility of biogas technology in Nigeria. The Usman Danfodiyo University in Sokoto designed a plant capable of producing 425 liters of biogas per day, sufficient for basic cooking needs.[106] In Ibadan, Oyo State, a biogas plant was developed for electricity generation using cassava peels and cow dung.[107] The Ikorodu Mini Abattoir in Lagos State implemented a biogas plant in 2019, converting organic waste through four 5000-liter digester tanks to power the abattoir for nearly six hours daily.[107] These projects demonstrate the potential for biogas to address energy needs in both rural and urban settings. However, issues such as deforestation arise from the utilization of some biomass materials. Deforestation, often due to clearing forests for residential and commercial fuel, is a significant contributor to climate change. The reliance on wood biomass, particularly in rural and low-income urban areas, has led to substantial forest depletion.[108] In addition to logging, agricultural expansion, fires, and other factors contribute to forest area loss. Nasiru Medugu *et al.*[109] report that Nigeria loses nearly 350 000 hectares of vegetation annually, while reforestation efforts cover only about 50 000 hectares per year.

Yet, Nigeria's underutilized biomass resources—including sewage, municipal waste, agricultural residues, and non-food energy crops—offer a unique opportunity. By repurposing these resources for bioenergy instead of relying on fossil fuels, Nigeria could reduce greenhouse gas emissions, mitigate climate change impacts, and generate sustainable electricity.[104,107]

3.3 Hydro energy

Nigeria is endowed with several waterfalls and major rivers, forming a vital component of its water resources.[110] According to Adeoti,[111] the nation has twelve water basins, which encompass numerous smaller rivers and waterways that maintain adequate minimum levels throughout the year. Currently, about 300 dams operate across the country,[112] collectively holding a capacity of 12 billion cubic meters (BCM) annually, primarily for agriculture, power generation, and raw water supply.[58] According to estimates, Nigeria possesses a water potential of approximately 286.6 BCM per year, including around 375.1 BCM per year of surface water resources and 88 BCM per year (24 percent) sourced from neighboring countries.[58]

The Federal Ministry of Power, Works and Housing, in their 2016 evaluation,[113] identified the River Niger, River Benue, and tributaries in the Niger Delta as potential sources for energy generation. Despite this, only about 15 percent of the total hydroelectricity potential, is currently being utilized.[23,24] Hydropower constitutes roughly 20% of the system's power supply and is the only RE source integrated into the national grid.[23,114] The three primary hydroelectric plants—Kainji, Jebba, and Shiroro—contribute approximately 1.9 GW of electricity to the national system.[115]

As of 2014, several additional power projects were underway, including Guarara II (360 MW), Kashimbilla (40 MW), Itisi (40 MW), Guarara I (30 MW), and the Mambila hydropower plant, which is expected to generate 3050 MW.[58] Despite these efforts, a significant portion of Nigeria's hydropower potential remains untapped. Harnessing hydropower as a RE source is crucial for ensuring a sustainable energy future and fostering a robust, energy-driven economy.

3.4 Solar energy

Solar energy, derived from the sun's rays, can be directly converted into heat or electricity using appropriate solar conversion devices. It is widely regarded as the most abundant and accessible RE resource. Nigeria is situated within the equatorial region's high solar belt, receiving an annual average solar radiation of 5.5 KW h per m^2 per day. Research indicates that the country enjoys over six hours of sunlight daily, with mean solar irradiation reaching 19.8 MJ per m^2 per day.[19]

Significantly, it is estimated that if solar modules were installed on just 1% of Nigeria's geographical area, they could generate more than 100 times the nation's current energy requirements. However, solar potential varies between regions; while some areas in northern Nigeria experience irradiation levels of up to 7 kW h per m^2 per day, coastal regions may have values as low as 3500 W h per m^2 per day.[58] The northern region, with an irradiation level exceeding 2000 kW h per m^2, is particularly well-suited for large-scale solar power development.[19,116] This potential is comparable to regions in Europe and the Americas where large solar technologies have been successfully deployed.[116]

Traditionally, Nigeria has utilized solar energy primarily for drying agricultural products and preserving goods such as meat and fish.[117] However, it is only in recent years that advancements in solar technology have enabled the generation of electricity from solar power. The country has limited experience with grid-connected solar projects, primarily relying on off-grid hybrid and standalone solar systems.[118] Most of these initiatives cater to minimal energy needs, such as powering public healthcare facilities, residential buildings, solar water pumps, streetlights, and refrigerators.[119,120] According to Ozoegwu *et al.*,[121] solar lighting currently illuminates over 100 streets in the federal capital city, Abuja. Similar solar streetlight projects are underway across the country, including a comprehensive installation in Kaduna, located in northwest Nigeria. The Energy Commission of Nigeria (ECN) has funded numerous solar initiatives in rural areas, with the Rural Electrification Agency (REA) reporting hundreds of solar projects established in these regions.

In recent years, Nigeria has made several noteworthy attempts to integrate solar power stations into its national electricity grid, in a bid to diversify its energy mix and address

Table 2 Summary of grid-connected solar power projects in Nigeria

Project name	Capacity (MW)	Location	Status	Developer/notes
Haske solar power plant	10	Challawa industrial estate, Kano	Commissioned (2023)	Largest operational grid-connected solar plant; NSIA-backed
Bayero university solar plant	3.5	Kano	Operational	Powers university; connected to grid
Federal university of agriculture, Makurdi	8.25	Benue state	Operational	Serves university and grid; Ministry of power project
Ganjuwa solar power plant	100	Bauchi state	Licensed	Nigeria solar capital partners Ltd
Gwagwalada solar power plant	143	FCT, Abuja	Licensed	Developed by enerlog Ltd
Middle band solar one solar PV park	157	Kogi state	Licensed	By Middle band solar one Ltd
Kankia solar PV project	75 (often cited as 100)	Katsina state	Under construction	Wärtsilä/Pan Africa solar JV; PPA signed with NBET
Katangar Lafiya solar plant	80	Dutse, Jigawa state	Licensed	Nova Scotia power development Ltd
Onyi solar power plant	50	Kokona, Nasarawa state	Licensed but cancelled	Afrinergia power Ltd
Argungu solar PV park	5600	Kebbi state	Early development	
Jigawa solar PV cluster	1000 (clustered)	Jigawa state	Under development	Part of solar power Naija and REA solar plans

its chronic electricity shortages (see Table 2). The most prominent example of successful grid integration is the Haske Solar Power Plant, a 10 MW facility commissioned in 2023 at the Challawa Industrial Estate in Kano.[122] Backed by the Nigerian Sovereign Investment Authority (NSIA), this plant stands as the country's largest operational grid-connected solar power project. Similarly, solar PV plants at Bayero University, Kano (3.5 MW) and the Federal University of Agriculture, Makurdi (8.25 MW) are operational and contribute directly to the grid while also powering their respective institutions.[123] These developments mark a turning point in Nigeria's RE journey, highlighting a growing willingness to harness its vast solar potential for grid-based electricity supply.

Beyond these operational plants, several other large-scale solar power projects have been licensed and are at various stages of development. Notable among them are the Ganjuwa solar power plant (100 MW) in Bauchi state, Gwagwalada solar power plant (143 MW) in Abuja, and the Middle band solar one PV Park (157 MW) in Kogi State—all licensed and awaiting full execution. In Katsina state, the Kankia solar PV project (75 MW), developed by a joint venture between Wärtsilä and Pan Africa solar, is currently under construction and has signed a Power Purchase Agreement (PPA) with the Nigerian Bulk Electricity Trading Plc (NBET). The Jigawa solar PV cluster, with an ambitious 1000 MW capacity, is part of a broader development plan under the Rural Electrification Agency's (REA) solar power Naija initiative. While the Onyi solar plant (50 MW) in Nasarawa was initially licensed, it has since been cancelled, pointing to the volatility and uncertainty that still plague project implementation.

Despite these encouraging developments, Nigeria continues to face formidable challenges in scaling grid-connected solar power, which have collectively slowed the realization of its full RE potential. Foremost among these is the fragile and underdeveloped transmission infrastructure, which remains incapable of efficiently evacuating electricity from many newly proposed or licensed solar power plants.[124] The national grid, managed by the Transmission Company of Nigeria (TCN), is often overloaded and experiences frequent breakdowns, with technical losses estimated at 7.4% as of 2022, according to the Nigerian Electricity Regulatory Commission (NERC).[125] As a result, even when new solar projects are technically ready for commissioning, grid capacity limitations often prevent timely interconnection. Another critical bottleneck lies in the regulatory and bureaucratic framework. RE developers frequently face extensive delays in securing approvals from multiple government agencies, including the NERC, the Rural Electrification Agency (REA), and the Federal Ministry of Environment (for Environmental Impact Assessments).[126] These layers of red tape inflate project timelines and discourage private sector involvement. For example, the Kankia solar PV project in Katsina State, originally targeted for completion in the mid-2010s, only began meaningful construction activities in recent years due to regulatory and financial delays.[126]

Power Purchase Agreements (PPAs)—crucial financial instruments for ensuring revenue certainty—remain a major area of concern. While NBET (Nigerian Bulk Electricity Trading Plc) has signed several PPAs with independent power producers, enforcement and timely payment remain inconsistent.[124] This lack of reliability in contract execution significantly undermines the bankability of solar projects, especially when developers seek long-term financing from international lenders. As a result, several licensed projects such as the Onyi solar plant (50 MW) in Nasarawa state have been stalled or cancelled due to lack of financial closure and market uncertainty.[116] In addition, Nigeria's solar industry faces limited local manufacturing capacity, which results in a heavy dependence on imported photovoltaic modules, inverters, batteries, and mounting structures. This reliance not only increases capital expenditure due to import duties and logistics costs but also exposes projects to global supply chain disruptions.[117] The National Agency for Science and Engineering Infrastructure (NASENI), for example, established the Karshi solar PV manufacturing plant in Abuja as part of Nigeria's strategy to reduce dependency on imported solar components and promote local content in RE development.[127,128] The plant was initially designed to produce polycrystalline silicon-based solar panels, with a reported installed capacity of approximately 7.5 MW per year. While the initiative aim to localize production, capacity remains low, and operational challenges persist due to underfunding and outdated equipment.[128] Access to affordable finance remains another major obstacle. Commercial banks in Nigeria generally classify solar infrastructure projects as high-risk ventures, often attaching high interest rates or declining long-term loan requests altogether.[112] Without concessional financing or guarantees from development finance institutions, many solar projects struggle to reach financial close. Furthermore, projects located in regions experiencing security threats or communal unrest—such as parts of the North-East and North-West—face additional risks including vandalism of equipment and attacks on personnel, which inflate insurance costs and deter foreign investment.

Yet, there has been a notable increase in awareness of solar technology, with more households and businesses installing solar PV systems to meet their energy needs. For instance, Lumos Nigeria, in collaboration with Mobile Telecommunication Networks (MTN), offers a lease scheme for PV power systems, allowing customers to pay a monthly subscription *via* their mobile phones until they own the system.[129]

Despite these promising developments, significant work remains to harness Nigeria's solar power potential fully.

3.5 Renewable energy policies in Nigeria

Nigeria's commitment to diversifying its energy portfolio and reducing dependence on fossil fuels has led to the development of a range of RE policies and legislative frameworks. These efforts are driven by the urgent need to address chronic electricity shortages, meet the country's growing energy demand, reduce greenhouse gas emissions, and expand energy access—particularly in underserved rural areas. While these policy efforts reflect a strong rhetorical commitment to sustainable energy, the practical implementation has often been marred by structural, financial, and institutional constraints.[127]

One of the cornerstone frameworks guiding Nigeria's RE ambitions is the REMP, developed in collaboration with the United Nations Development Programme (UNDP) and coordinated by the Energy Commission of Nigeria.[57] The plan aims to increase the share of RE in the national energy mix from 13% in 2015 to 23% by 2025 and 36% by 2030. This policy lays out a comprehensive strategy for harnessing solar, wind, biomass, and small hydropower resources and integrating them into both the national grid and decentralized energy systems. However, despite the plan's ambitious targets, implementation has been limited due to inadequate political will, lack of sustained financing, and poor monitoring frameworks. The targets outlined in the REMP appear more aspirational than operational, reflecting a broader trend of policy-practice disjunction in Nigeria's energy landscape. Complementing the REMP is the NREEEP, which was introduced in 2015.[130] This policy provides a broader framework for the promotion of both RE and energy efficiency. It emphasizes the creation of an enabling environment for private sector participation through regulatory incentives and access to financing mechanisms. According the Ozoegwu and Akpan,[57] the NREEEP also advocates for the development of off-grid RE solutions, particularly for rural communities. Nevertheless, while the policy is comprehensive in scope, it suffers from weak institutional coordination and a lack of enforcement authority. Additionally, state-level implementation remains negligible, as subnational governments are often excluded from decision-making and funding allocation. This disconnect between federal policy formulation and local execution severely limits the potential for RE deployment in the country.

The Electric Power Sector Reform Act (EPSRA) of 2005 marked a significant shift in the structure of Nigeria's power sector by introducing liberalization and encouraging private sector participation.[131] Though primarily focused on restructuring the power sector, the Act has had a profound impact on RE development. It established the Nigerian Electricity Regulatory Commission (NERC), which oversees all aspects of electricity regulation, including the facilitation of Independent Power Producers (IPPs). One of the key RE-specific instruments introduced under the EPSRA is the Renewable Energy Feed-in Tariff (REFiT) regulation in 2015. This initiative was designed to guarantee fixed tariffs for electricity generated from renewable sources, thereby providing long-term revenue certainty to investors. However, the REFiT has seen limited success due to the lack of credible power purchase agreements, insufficient grid infrastructure to absorb variable RE, and a general lack of investor confidence in regulatory consistency. The challenges facing EPSRA highlight the difficulties of implementing sector-wide reforms without parallel investments in institutional capacity and infrastructure upgrades.

The National Energy Policy (NEP), first introduced in 2003, provides an overarching vision for Nigeria's energy future.[132] It emphasizes the development of alternative energy sources to promote environmental sustainability and energy security. One of the notable provisions of the NEP is the establishment of the Rural Electrification Fund, which is intended to support off-grid RE projects. The policy recognizes the importance of decentralized energy systems in bridging Nigeria's energy access gap. However, like other frameworks, the NEP has not been revised to align with recent technological advances, climate goals, or Nigeria's commitments under international agreements such as the Paris Accord. Its continued relevance is undermined by outdated strategies and a lack of actionable timelines.

More recently, the Petroleum Industry Act (PIA) of 2021 has introduced a new dynamic into Nigeria's energy governance framework.[54] Although primarily aimed at reforming the oil and gas sector, the Act includes provisions that could support the RE transition. Section 64 of the Act mandates NNPC Limited to collaborate with private investors to develop RE resources. This clause offers a legal foundation for mainstreaming renewables within the operations of Nigeria's dominant energy players. Moreover, the Act introduces funding mechanisms that could be redirected toward clean energy projects, potentially leveraging oil revenue to catalyze Nigeria's energy transition.[54] Nonetheless, the practical realization of these provisions depends heavily on political commitment and the willingness of fossil fuel stakeholders to invest in long-term structural change—a prospect that remains uncertain given entrenched interests in the petroleum sector.

In 2022, Nigeria unveiled its ETP, which is arguably the most forward-looking and internationally aligned policy in the country's RE space.[41] The plan sets a target of net-zero emissions by 2060, with a commitment to generate 30 GW of RE capacity by 2030. Solar energy, in particular, is positioned as the backbone of this transition, with plans to deploy 5 GW of solar power to expand energy access and reduce emissions. The ETP reflects Nigeria's evolving recognition of the global energy transition and its own domestic development needs. However, its ambitious targets are heavily reliant on international financing and carbon market mechanisms, which introduces uncertainties regarding funding consistency and donor alignment. Moreover, the plan's success hinges on addressing foundational issues such as weak transmission infrastructure, poor data availability, and limited technical capacity.[41] In parallel, Nigeria's decentralized RE policy approach has gained traction through the efforts of the Rural Electrification Agency (REA).[133] Programs such as the Nigeria Electrification Project (NEP), supported by the World Bank and African Development Bank, have scaled up the deployment of mini-grids and solar home systems in off-grid communities.[51] These initiatives have contributed to the reduction of energy poverty, job creation, and local economic development. While encouraging, these efforts are still fragmented and lack a unified regulatory framework, making it difficult to scale them beyond donor-funded models.

The Climate Change Act of 2021 further strengthens the legal landscape for RE by mandating the development of sectoral carbon budgets and requiring ministries and agencies to align their activities with national climate targets.[134] The Act provides a platform for integrating environmental sustainability with economic planning and places additional pressure on the energy sector to decarbonize. However, as with many Nigerian laws, enforcement remains a challenge. The institutional arrangements to operationalize the Act are still nascent, and coordination among stakeholders is limited.

Additionally, the National Action Plan on Gender and Renewable Energy, introduced in 2020, seeks to bridge gender gaps in energy access and participation.[135] It promotes the inclusion of women in the RE value chain and supports female entrepreneurship in clean energy technologies. While this policy adds a much-needed socio-economic dimension to energy policy, its impact is constrained by broader structural issues such as lack of access to capital, social norms, and limited education and training opportunities for women in technical fields.

The enactment of the Electricity Act 2023 also represents a transformative milestone in Nigeria's power sector reform and holds significant implications for RE development.[136] This Act repeals the longstanding Electric Power Sector Reform Act (EPSRA) of 2005 and introduces a more decentralized structure by empowering states, private entities, and local governments to generate, transmit, and distribute electricity within their jurisdictions. Critically, the Act recognizes RE as a strategic pillar for electrification, particularly in rural and underserved communities, and seeks to mainstream decentralized RE systems such as mini-grids and standalone solar solutions. It provides legal backing for the licensing of small-scale RE providers, encourages embedded generation, and promotes competitive electricity markets that can support clean energy investments. By creating a more flexible and enabling regulatory environment, the Electricity Act 2023 addresses some of the bottlenecks that have historically hindered RE deployment in Nigeria.[41] However, its successful implementation will depend on the technical capacity of state governments, the harmonization of subnational electricity regulations, and the ability of the Nigerian Electricity Regulatory Commission (NERC) to coordinate effectively with new market actors. If these challenges are adequately managed, the Act could serve as a catalyst for Nigeria's energy transition and significantly enhance energy access through renewable sources.

While Nigeria has developed an impressive array of RE policies and legislative frameworks, the effectiveness of these instruments has been undercut by systemic issues, including weak implementation, regulatory fragmentation, and inadequate financing.

4 Comparative analysis: Nigeria *vs.* other emerging economies

Despite possessing some of the highest solar radiation levels in Africa and abundant wind, hydro, and biomass resources, Nigeria remains heavily dependent on fossil fuels. There are clear evidence that the country's RE policy framework is fragmented, investments are low, and infrastructure remains inadequate, compared to other emerging countries such as Kenya, South Africa, India, *etc.* Some comparative analyses are made in this section (see Table 3).

4.1 Policy framework: fragmentation *vs.* strategic vision

Yetano Roche *et al.*[170] note that Nigeria's RE policy framework suffers from fragmentation, weak enforcement, and a lack of long-term strategic vision, which hinders the sector's development. While the Renewable Energy Action Plan (REAP) of 2005, the National Energy Policy (NEP) of 2017, and the Electricity Act of 2023 provide broad directives but fail to establish enforceable RE targets,[171] unlike the structured policies seen in South Africa and Kenya. According to Babayomi *et al.*,[51] Nigeria's import duty waivers for solar panels and mini-grid incentives aim to attract investors but the absence of a legal framework that mandates RE adoption levels or procurement quotas discourages large-scale investments. Thus, the Electricity Act (2023) has opened

Table 3 Comparative analysis of renewable energy development across selected countries

Criteria	Nigeria	South Africa	Kenya	India	China	Germany
RE contribution to energy mix (%)	20% (majority hydro)[114]	17% (majority wind & solar increasing)[137]	80% (geothermal leader)[138]	46.3% (large solar & wind projects)[139]	35% (world's RE leader)[140]	50%+ (strong wind, solar, hydro) (see Fig. 3 also)[141]
RE capacity (GW)	2.1 (see Fig. 5)[142]	10.62 (see Fig. 5)[142]	2.74 (see Fig. 5)[142]	176 (see Fig. 4)[143]	1453 (see Fig. 4)[143]	167 (see Fig. 4)[143]
Investment in RE (USD per year)	$1B	$2B	$3.2B (ref. 144)	$12.4B (ref. 145)	$273B (see Fig. 6)[145]	$36.6B (ref. 145)
Key policy incentives	Import duty waivers, loans, tax breaks (weak enforcement)[146]	Tax reductions, dedicated RE independent power producer procurement program (REIPPPP),[147] increased investment allowances for electric vehicles[148]	Feed-in tariffs, net metering, Kenya vision 2030, energy efficiency policies[149]	Government subsidies, net metering, feed-in tariffs, production linked incentive (PLI) schemes, energy efficiency targets, and viability gap funding[150,151]	Government-backed subsidies, renewable portfolio standards (RPS), building a strong reliability network frame, energy efficiency standards, feed-in tariffs[152]	Feed-in tariffs, tax benefits for investments in RE, and government loans and grants for RE projects[153,154]
Grid integration	Weak (frequent power cuts) with limited grid capacity to incorporate large amounts of RE[155]	Steadily increasing. Around 7.3% of the total electricity generation[156]	Very high level of grid integration with RE, with approximately 90% of its electricity[157]	6% RE penetration[158]	Highly installed capacity, although there are grid bottlenecks[159]	Fully developed (around 50% of total electricity generation)[160]
Off-grid solutions	Growing, but financing limited[161]	Expanding mini-grid sector especially due to recent grid instability and power outages[162]	Strong especially in rural areas[163]	Off-grid solar booming[164]	Large-scale off-grid electrification[165]	Germany is a leader in off-grid solar, wind, and hydropower systems in europe[166]
Local manufacturing of RE materials	Very low, still developing[94]	Some capacity for wind/solar panels, however, the level of local production remains relatively low compared to the overall demand[156]	Moderately low (solar components made locally)[138]	Developing domestic manufacturing (solar, wind) and a substantial reliance on imported components, particularly for solar panels[167]	World's largest RE manufacturer[168]	Advanced (exporter of RE technology)[169]

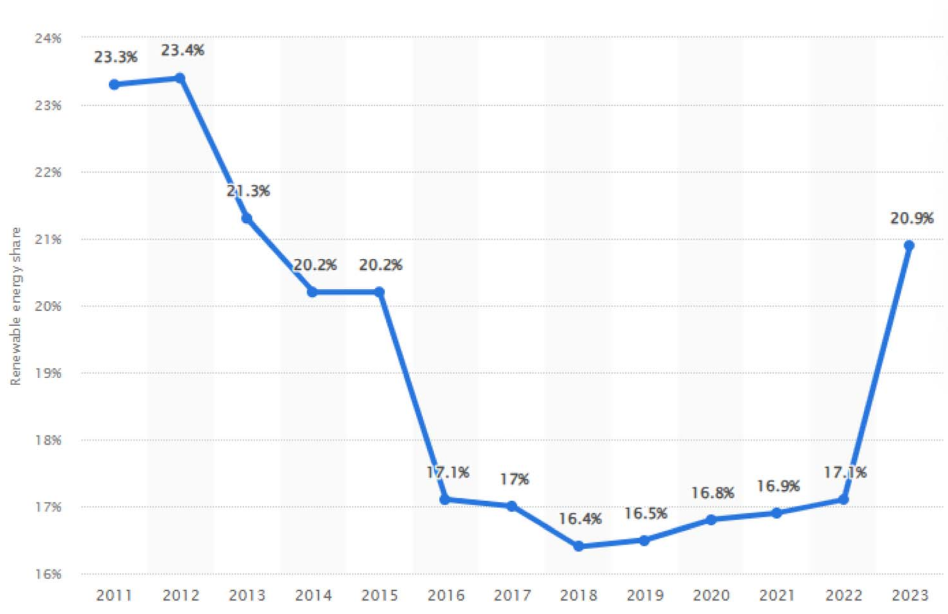

Fig. 2 Renewable energy share in Nigeria.[114]

up opportunities for states to regulate their electricity markets, but grid integration challenges, poor policy coordination, and uncertainty surrounding power purchase agreements (PPAs) continue to discourage independent power producers (IPPs) from investing in large-scale renewable projects.[43] Unlike South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), which provides a more transparent and competitive framework for private investment,[172] Nigeria's policies fail to offer structured incentives or guarantees, resulting in a low RE contribution of 20% to its energy mix (see Fig. 2),[114] compared to Kenya's 80%.[138]

South Africa's Integrated Resource Plan (IRP) and REIPPPP stand out as a structured model for attracting RE investments. According to Leigland and Eberhard,[172] the REIPPPP has

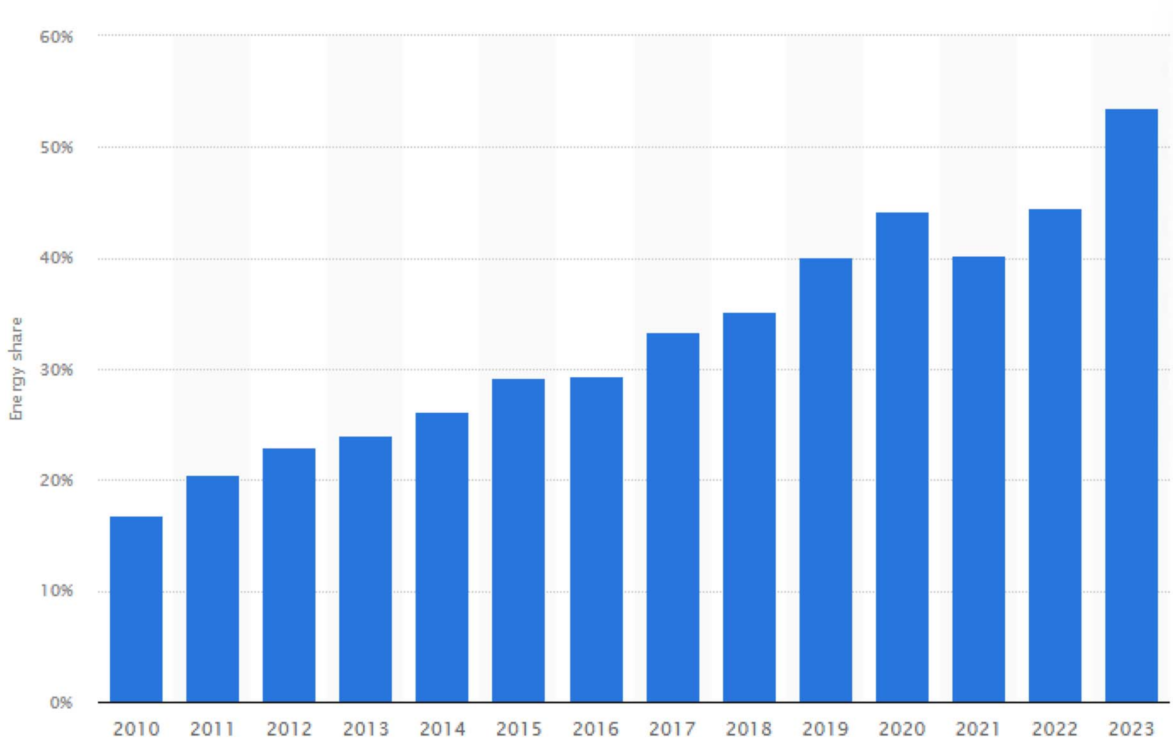

Fig. 3 Contribution of renewable energy to Germany's energy mix.[141]

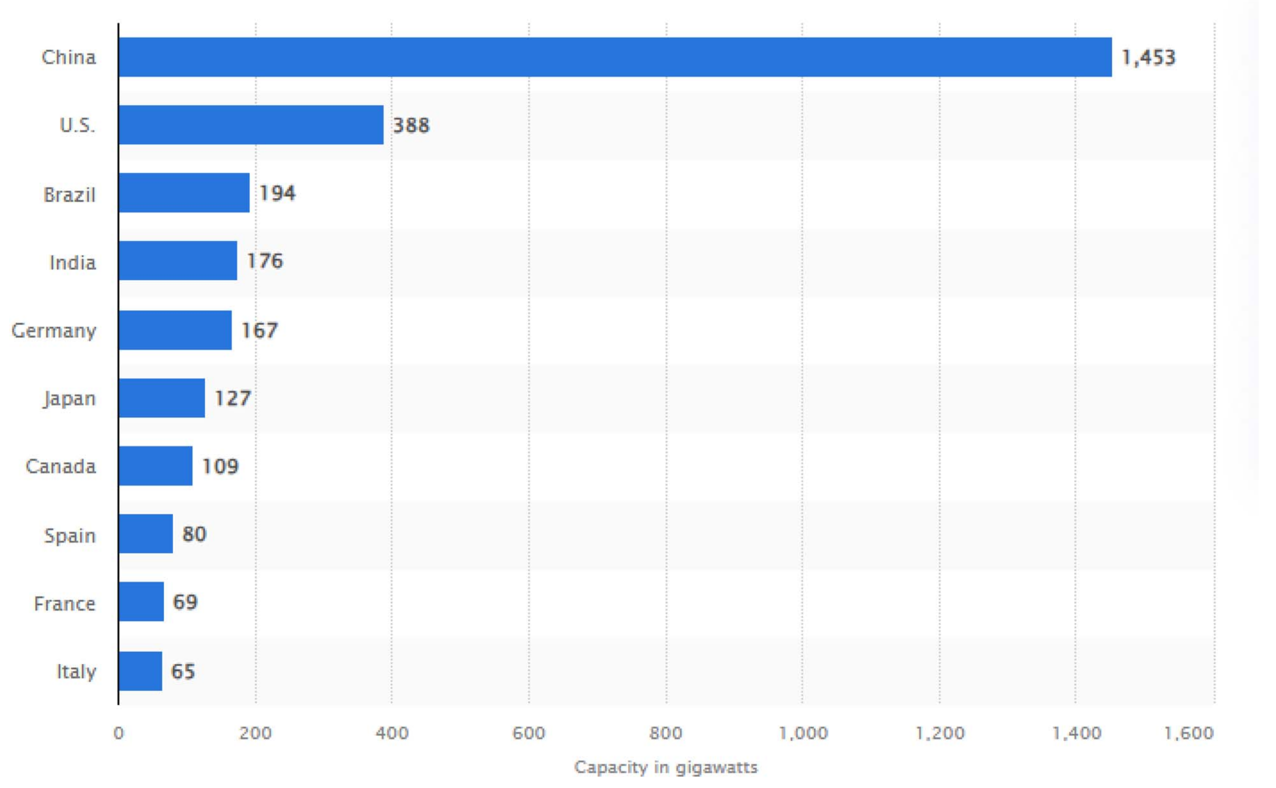

Fig. 4 Renewable energy capacity for leading countries.[143]

mobilized over $16 billion in private investments since 2011, making South Africa a leader in RE deployment in Africa. The country's policy-driven approach ensures competitive bidding, clear PPA frameworks, and financial de-risking for IPPs, which has led to the development of more than 6000 MW of RE projects. However, Hanto *et al.*[173] assert that Eskom's dominance in electricity generation and transmission has led to delays in REIPPPP implementation, with several projects stalled due to transmission bottlenecks and financial instability within Eskom. Despite these setbacks, South Africa has a well-defined roadmap for integrating RE into its national grid, unlike Nigeria. The lack of legal mandates requiring utilities to procure a certain percentage of their power from renewables, as seen in South Africa's procurement framework, undermines Nigeria's ability to scale up RE adoption at a national level.

Kenya, on the other hand, has successfully leveraged feed-in tariffs (FiTs) and off-grid incentives to drive private sector growth in RE, particularly in the mini-grid and geothermal sectors.[174] The Energy Act (2019) streamlined the country's RE regulatory framework, removing bureaucratic bottlenecks and offering attractive incentives for developers. As a result, Kenya generates over 80% of its electricity from renewable sources, with geothermal alone contributing over 28%.[175] Unlike Nigeria, where inconsistent government support has stalled large-scale RE development, Kenya's FiT model provides guaranteed pricing for RE producers, encouraging long-term investments.[149] However, Kenya's RE sector remains heavily dependent on geothermal energy, with limited diversification into wind and solar. Despite this limitation, Kenya's proactive policy environment, decentralized regulatory framework, and strong focus on rural electrification have positioned it as a regional leader in RE adoption. Nigeria must learn from Kenya's targeted policy approach, particularly in the area of mini-grid development and off-grid solar expansion, to improve electricity access in underserved regions.

4.2 Investment levels

Again, Nigeria's RE investment remains disproportionately low compared to its economic size and energy needs. In 2023, Nigeria invested only $1 billion in RE investments, significantly trailing behind South Africa ($2 billion) and Kenya ($3.2 billion).[144] This disparity stems largely from policy uncertainty, regulatory inconsistencies, and inadequate financial incentives that deter private sector participation. Investors require clear policy commitments, stable power purchase agreements (PPAs), and well-defined risk mitigation frameworks, all of which are lacking in Nigeria. The private sector plays a minimal role in Nigeria's RE development, largely due to regulatory uncertainty and the dominance of government-controlled electricity infrastructure. Unlike South Africa, where IPPs contribute significantly to large-scale wind and solar projects,[172] Nigeria's private sector faces limited financial incentives, long project approval timelines, and difficulties securing grid connections. While Kenya has leveraged public–private partnerships (PPPs) and innovative financing models to scale its geothermal and mini-grid projects, Nigeria's RE financing landscape remains

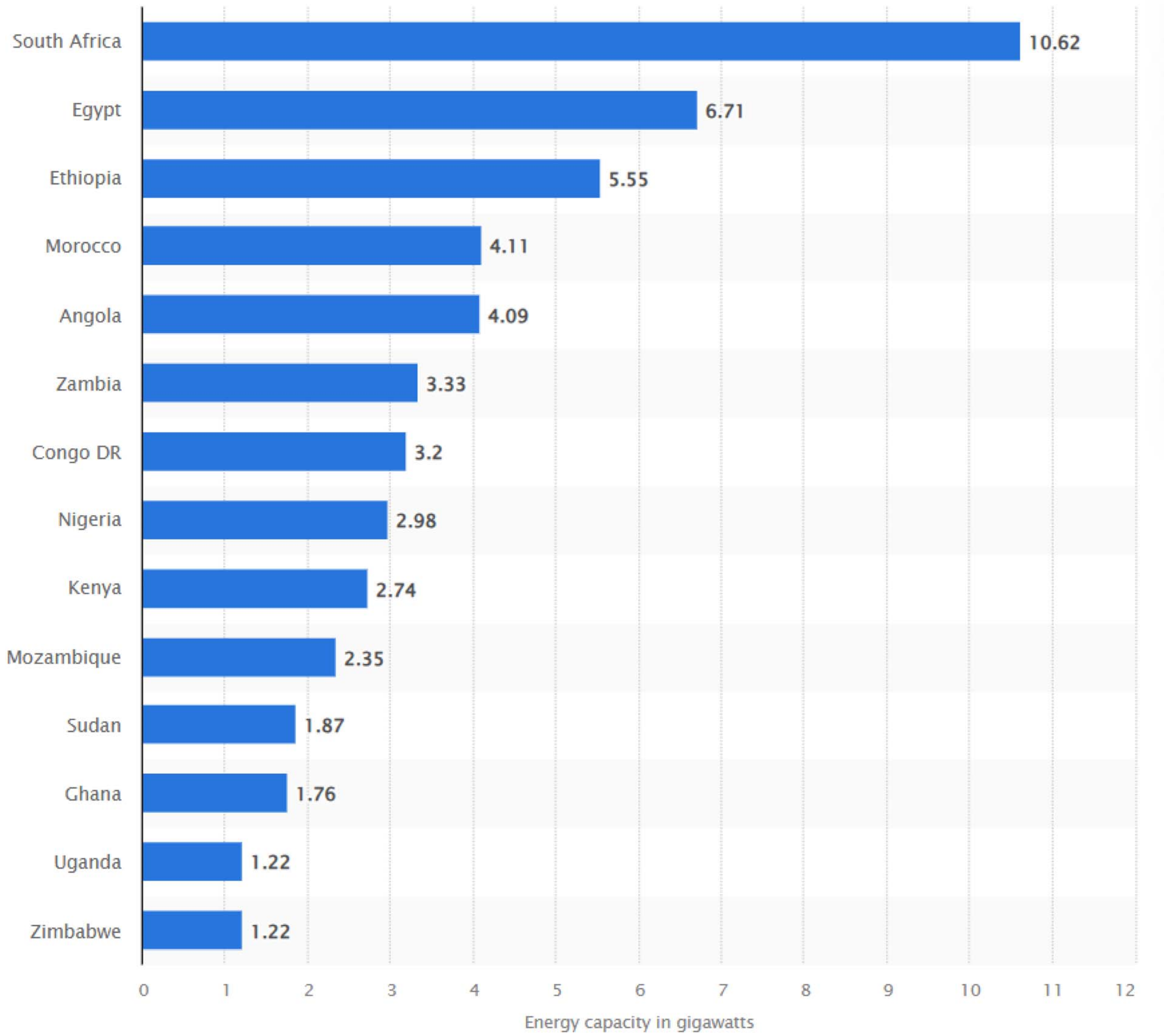

Fig. 5 Renewable energy capacity for African countries.[142]

heavily reliant on donor funding.[146] For example, Kenya's Scaling Solar program, supported by the World Bank, has successfully reduced project risks and attracted significant private capital.[176] Meanwhile, Nigeria's lack of risk-mitigation frameworks, high import tariffs on RE equipment, and weak domestic manufacturing capacity make renewable projects financially unappealing.[177] Without clear policy direction, stronger financial incentives, and improved regulatory stability, Nigeria will continue to fall behind its African counterparts in RE investment, despite having one of the largest untapped RE markets on the continent.

4.3 RE adoption

As earlier established, RE adoption in Nigeria remains sluggish, with only 20% of its electricity coming from renewables, primarily hydropower, which is vulnerable to climate variability and seasonal fluctuations. In stark contrast, Kenya has achieved an 80% RE share, largely due to its strategic investment in geothermal energy and a robust mini-grid solar sector that has electrified rural communities.[138] Meanwhile, South Africa, despite its historical reliance on coal, has significantly expanded wind and solar power, adding over 6000 MW of renewables since 2011 through its REIPPPP.[137] Nigeria's failure to diversify its RE mix, streamline policy implementation, and provide clear investment incentives has resulted in a stagnant RE sector, while solar and wind projects remain underdeveloped.

4.4 Off-grid solutions

Nigeria's off-grid RE sector is expanding but remains severely constrained by financing challenges.[161] Despite high electricity deficits (over 85 million Nigerians lack grid access) and the government's push for mini-grid development, limited access to low-interest financing, high import costs for solar components, and weak policy enforcement continue to hinder large-scale adoption.[58,161] In contrast, South Africa's mini-grid sector has

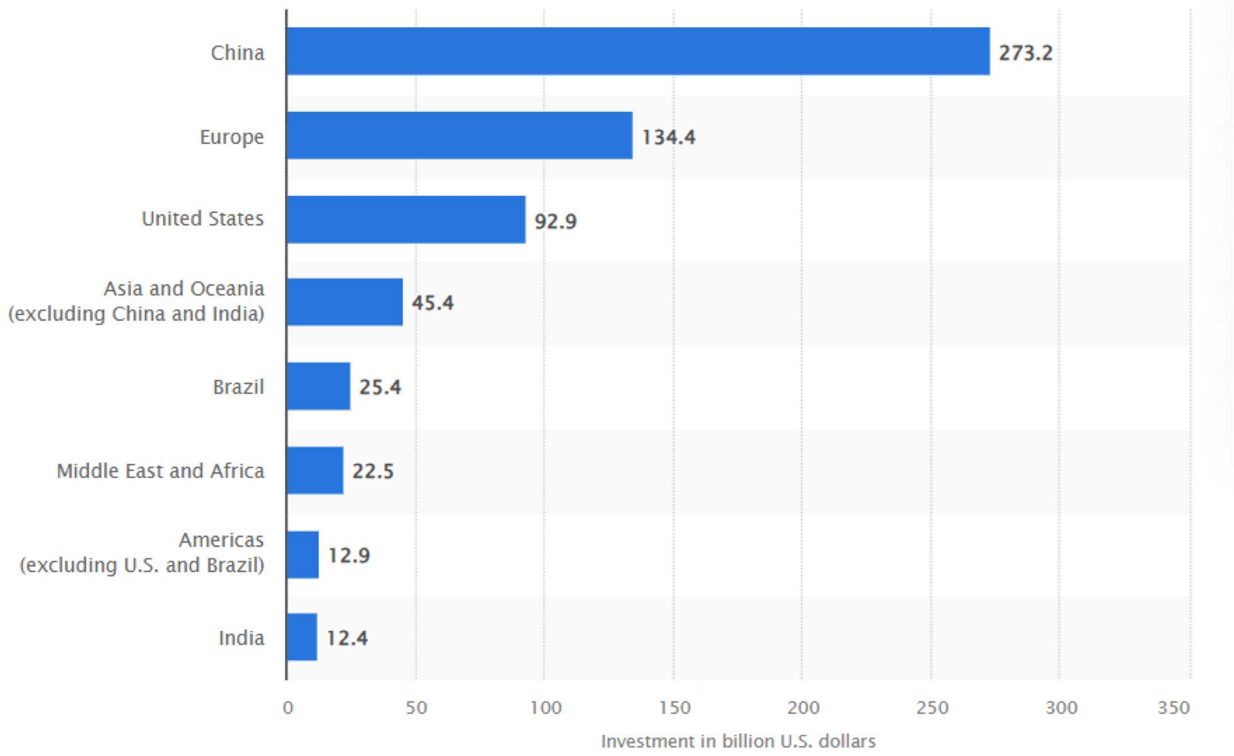

Fig. 6 Investments by region.[145]

grown rapidly, driven by worsening grid instability and frequent power outages, which have made decentralized energy solutions more viable.[162] Kenya stands out as a leader in off-grid electrification, with over 250 mini-grids and strong private-sector participation ensuring widespread rural energy access.[163] Meanwhile, India's off-grid solar market is booming, with government-backed subsidies, micro-financing schemes, and corporate partnerships facilitating the deployment of solar home systems, microgrids, and community solar projects.[164] Unlike India and Kenya, Nigeria lacks a well-structured financing mechanism to support off-grid solar deployment, relying heavily on international donor funding rather than long-term domestic investment strategies.

Table 3 provides a comparative summary of Nigeria's RE development with some emerging and developed countries.

5 Materials used for renewable energy technologies in Nigeria

This section examines the various materials and technologies for RE employed in Nigeria. By examining these materials and their applications, we can gain insight into the potential for RE technologies to transform Nigeria's energy landscape.

5.1 Solar energy

In Nigeria, solar energy technologies primarily employ materials for PV systems and solar thermal applications, which can be broadly categorized into semiconductors, structural materials, and energy storage solutions. Here are some common materials used in each category:

5.1.1 Silicon (Si). Silicon dioxide (SiO_2), commonly known as silica, serves as a fundamental material in solar cell manufacturing. Silicon (Si), identified by its chemical symbol, is the second most abundant element in the Earth's crust after oxygen.[178] Natural sources of silicon include sand, quartzite, mica, and talc, with sand being the most commonly exploited ore for extraction.[179] Silicon is classified as a brittle metalloid, possessing a metallic luster and a specific gravity of 2.42 at 20 °C. It crystallizes in a diamond lattice structure and exists in various natural silicate and silicon dioxide forms. To obtain high-purity, metallurgical-grade silicon essential for solar panel production, silica undergoes a high-temperature reduction process in the presence of carbon to remove oxygen.[180,181]

Nigeria is endowed with significant silica deposits across various states, including Lagos, Ondo, Kano, Jigawa, Rivers, and Delta.[182] Nationwide, silica sand is abundantly available in at least 25 states, with the most substantial deposits concentrated in southern Nigeria. Given this resource availability, Nigeria has the potential to establish a sustainable supply chain for silicon-based solar cells. Recognizing this potential, NASENI, in collaboration with the China Great Wall Industry Corporation (CGWIC), has initiated the development of a solar cell production facility in Gora, Nasarawa State.[183] This initiative represents a major advancement, complementing the efforts of NASENI Solar Energy Limited (NSEL), which currently manufactures solar PV modules.

5.1.2 Thin-film materials (CdTe, CIGS). The production of thin-film solar panels in Nigeria presents a promising avenue for enhancing the country's RE sector. Thin-film PV technology, which includes materials such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si), offers advantages such as lower production costs, greater flexibility, and improved performance in diffuse light conditions.[184–187] Unlike conventional crystalline silicon panels, thin-film solar cells require fewer raw materials and can be integrated into diverse applications, including building-integrated photovoltaics (BIPV).[188] The abundance of key raw materials, particularly silica and aluminium, coupled with Nigeria's strategic ambition to localize RE technologies, underscores the viability of developing a thin-film solar panel manufacturing industry.

As highlighted earlier, Nigeria possesses significant reserves of silica, a crucial component in the production of amorphous silicon thin-film panels. Additionally, the country has bauxite reserves in states such as Plateau and Adamawa, which are essential for aluminium extraction—another vital material in thin-film solar module frames and conductive layers.[189] The key elements of CIGS—copper, indium, gallium, and selenium—are present in various forms across Nigeria but require significant processing capabilities. Copper is abundant, with major deposits found in Zamfara, Bauchi, and Nasarawa states.[190] Indium and gallium, typically recovered as byproducts of zinc and bauxite processing, remain largely untapped in Nigeria due to the lack of advanced refining facilities.[191,192] Selenium, another critical component, is often sourced from copper refining, which is not widely developed in the country. Despite these natural advantages, Nigeria has yet to establish a robust value chain that can transform these raw materials into commercially viable solar products. The absence of large-scale processing facilities for high-purity silicon and other semiconductor materials remains a bottleneck, necessitating strategic investments in refining and fabrication capabilities. Nigeria, like many African countries, largely relies on imported solar PV technology and components.

5.1.3 Perovskite materials. Although in early stages, perovskites promise high efficiency and flexibility.[193–195] Lead, a primary component of many perovskite solar materials, is widely available in Nigeria, with major deposits in states such as Ebonyi, Benue, and Zamfara.[196,197] Despite the availability of this resource, challenges such as illegal mining and environmental hazards associated with lead extraction must be addressed before it can be sustainably utilized for perovskite solar applications.[198] Additionally, efforts must be made to refine and purify lead to meet the stringent requirements for solar-grade materials. Iodine, another critical element in perovskite solar cells, is not naturally abundant in Nigeria and would require importation or synthetic production from available bromine resources, which have been identified in Nigeria's sedimentary basins.[199]

Beyond raw material sourcing, establishing a production pipeline for perovskite solar panels in Nigeria will require substantial investment in research, material processing, and fabrication infrastructure. While some Nigerian researchers have begun investigating perovskite synthesis and stability improvements,[200,201] there is a need for stronger collaboration between academia, industry, and government agencies to translate research findings into commercial applications. If properly harnessed, perovskite solar technology could provide a viable pathway for Nigeria's transition to locally manufactured high-efficiency solar panels, reducing dependency on imported PV modules.

5.1.4 Ethylene-vinyl acetate (EVA). Ethylene-vinyl acetate (EVA) is a crucial element in the manufacturing of solar PV modules, serving as the encapsulant that binds all components—except the frame—into a single unit during lamination.[202] Its primary function is to shield solar cells from harsh environmental conditions, thereby enhancing the durability and efficiency of the panels. The composition of EVA typically consists of approximately 11% vinyl acetate, while the remaining 89% comprises ethylene, which dictates its flexibility and adhesion properties.[203] There is no evidence of production in Nigeria; most EVA used in Nigeria is imported from other nations like the United States and China. The production of EVA in Nigeria, however, presents significant potential, given the availability of ethylene, a key raw material. Ethylene can be sourced from the Idorama Eleme Petrochemical Plant in Rivers State, where polyethylene is derived from ethylene through advanced petrochemical processing.[204] This local supply chain can serve as a foundation for EVA production, reducing dependence on imports and fostering domestic manufacturing growth.

The necessary infrastructure and expertise to process ethylene into EVA sheets for solar module encapsulation are attainable within Nigeria. However, to achieve large-scale production, investments in polymer processing facilities and specialized manufacturing plants are essential. The establishment of such facilities would support the RE sector, creating job opportunities while promoting technological advancements in solar PV module production. By leveraging its petrochemical resources, Nigeria can position itself as a hub for EVA production, not only for local consumption but also for export to other solar energy markets in Africa. With appropriate policy support, investment incentives, and industrial collaborations, the country can enhance its self-sufficiency in solar technology manufacturing, contributing significantly to its broader RE ambitions.

5.1.5 Polyvinyl fluoride (PVF). Polyvinyl fluoride (PVF), commercially known as Tedlar Polyester Tedlar (TPT), is a crucial backsheet material in PV modules, ensuring electrical insulation and shielding internal components from environmental degradation.[205] Designed to withstand ultraviolet (UV) exposure, moisture, and mechanical wear, TPT enhances the durability and operational lifespan of solar panels.[206] Typically composed of highly reflective and opaque films, it prevents internal layers from deteriorating due to prolonged sunlight exposure. Given Nigeria's established petrochemical industry, the country has the potential to develop the necessary raw materials for TPT production, reducing dependence on imports and supporting local solar PV manufacturing.

5.1.6 Glass and polymers. A crucial component of solar PV modules is tempered glass, which acts as a protective barrier against environmental elements such as moisture, dirt, and other potential contaminants that could degrade solar cells.[207] The primary raw material for glass production is silica, derived from silicon dioxide (SiO_2), a compound shown to be abundant in Nigeria, as detailed in various studies. Despite the vast availability of silica sand resources suitable for glass manufacturing, Nigeria continues to rely heavily on imports. According to the United Nations COMTRADE database on international trade as highlighted in Trading Economies,[208] Nigeria spent about US$32.41 million in 2023 on the imports of glass and glassware. Reports from the Raw Materials Research and Development Center (RMRDC) and other relevant agencies such as the Federal Institute of Industrial Research, Oshodi (FIIRO) highlight the feasibility of local tempered glass production for solar PV modules.[209] However, despite the established potential, investors have yet to capitalize on this opportunity to develop domestic production facilities that would support Nigeria's indigenous solar PV manufacturing sector.

5.1.7 Aluminum and steel for mounting. Lightweight aluminum and corrosion-resistant steel are common in framing and mounting systems, which are essential for long-term stability and energy capture.[210,211] Aluminium, a key element in Group 13 of the periodic table, is a lightweight, silvery-white metal widely found in the Earth's crust.[212] One of its primary sources is bauxite, a naturally occurring ore with a high aluminium content. Nigeria is endowed with significant bauxite deposits, particularly in Plateau, Ondo, Ekiti, and Adamawa states.[191,192]

Aluminium production relies on two main sources: recycled aluminium scrap and primary aluminium.[213] The latter involves a sequence of industrial processes, including bauxite extraction, alumina refining, electrolytic reduction, and casting of primary ingots. In solar PV module manufacturing, aluminium alloy 6063, part of the 6000-series alloys, is widely used for constructing panel frames.[214] This preference is due to its lightweight properties and strong resistance to corrosion, both of which are essential for ensuring durability in solar installations. Given the substantial availability of aluminium resources in Nigeria, there is considerable potential for the local production of solar PV components. However, to harness this opportunity, increased investment in aluminium processing and solar-related industries is necessary to reduce dependency on imported materials and stimulate domestic manufacturing.

5.2 Wind energy

Wind energy technology relies on specific materials that ensure turbine efficiency, resilience, and durability under varying environmental conditions. Key materials include:

5.2.1 Fiberglass composites. Fiberglass-reinforced composites are widely regarded as the standard material for wind turbine blade manufacturing due to their excellent balance of strength, flexibility, and lightweight properties.[211,215,216] These materials are particularly suited for the demanding structural requirements of wind energy applications, as they provide high resistance to mechanical stress, fatigue, and environmental degradation. In Nigeria, where wind turbine installations must withstand varying climatic conditions—including high humidity, coastal salinity, and seasonal harmattan dust—fiberglass composites offer a durable and cost-effective solution.[217] Their corrosion resistance is particularly critical for wind farms in regions such as Lagos, Delta, and Rivers states, where exposure to moist and saline air could rapidly degrade metal-based alternatives.[218] Additionally, the ability of fiberglass composites to be molded into aerodynamic blade shapes ensures optimal energy capture from Nigeria's moderate wind speeds, making them indispensable for the country's wind energy sector.

Despite the advantages of fiberglass composites, Nigeria currently relies on imports for most of the raw materials including glass fibers, resin matrices, and curing agents. However, there is potential for local manufacturing if the country invests in developing its glass fiber industry, particularly using the abundant silica sand deposits.[219] Additionally, resin production can be strengthened through Nigeria's established petrochemical sector, particularly in areas like Port Harcourt and Warri, where polymer-based industries are already operational.[220] Research institutions and private sector collaborations could accelerate the local production of fiberglass composites, reducing reliance on imports and fostering a more sustainable supply chain for wind turbine blade manufacturing.

Carbon fiber composites are an advanced material option for manufacturing high-performance wind turbine blades due to their superior strength-to-weight ratio compared to fiberglass.[221] These materials exhibit exceptional tensile strength, stiffness, and fatigue resistance, making them ideal for larger and more efficient wind turbines.[211,221,222] The lower density of carbon fiber allows for the production of longer and lighter blades, which improves aerodynamic efficiency and energy capture, especially in regions with moderate to low wind speeds.[221] However, the high cost of carbon fiber remains a major barrier to widespread adoption in Nigeria's wind energy sector.[223] Unlike fiberglass composites, which have some potential for local production due to the availability of silica sand for glass fiber reinforcement, carbon fiber production requires advanced polymer processing techniques and precursor materials such as polyacrylonitrile (PAN) or pitch-based fibers, which are not yet produced domestically at scale.[221] Nigeria's petrochemical industry could play a role in the development of precursor materials, particularly in regions with established polymer manufacturing capabilities like Port Harcourt and Warri.

5.2.2 Steel. Steel remains the backbone of wind turbine tower construction due to its unmatched strength, resilience, and ability to support massive structures under varying wind conditions.[224] Its high load-bearing capacity ensures that turbines remain stable even at great heights, which is essential for maximizing energy capture, particularly in areas with lower wind speeds.[225] Nigeria, with its growing industrial sector, has significant potential to source and process steel locally for turbine tower manufacturing. The country boasts vast iron ore deposits, particularly in Kogi, Enugu, and Kaduna states, which, if fully harnessed, could reduce reliance on imported steel and lower production costs. The presence of steel manufacturing plants, such as Ajaokuta Steel Company and smaller rolling mills across the country,[226] presents an opportunity for localizing wind energy infrastructure and stimulating domestic industries. However, the challenge lies in reviving and modernizing these steel plants to meet the high-quality standards required for wind turbine towers, as inconsistencies in steel production could affect the structural integrity of the towers over time.[227]

Beyond availability, the economic and logistical factors surrounding steel production in Nigeria must be critically examined. While steel can be locally sourced, Adegbite and Adegbite[226] contend that the industry has suffered from underinvestment, inconsistent power supply, and policy inefficiencies, limiting its capacity to meet large-scale demand. Importing high-grade steel remains a costly alternative, further complicating the financial feasibility of wind energy projects. Additionally, the transportation of heavy steel components to installation sites, particularly in rural or off-grid areas, presents infrastructural challenges due to poor road networks and limited rail transport.[226] Addressing these issues requires government intervention through policy reforms, investment in steel processing technologies, and strategic partnerships with international firms to enhance local production capabilities.[226–228] If these hurdles can be overcome, locally produced steel for wind turbine towers could not only support Nigeria's RE ambitions but also create jobs, reduce foreign exchange expenditure on imports, and position the country as a leader in wind energy development in West Africa.

5.2.3 Concrete. Concrete has emerged as a viable alternative to steel for onshore wind turbine towers, particularly in regions where transporting large steel components is logistically challenging and expensive.[229–231] Unlike steel, which requires specialized manufacturing and precise assembly, concrete towers can be produced and assembled closer to installation sites, reducing transportation costs and project delays.[230] This is especially relevant in Nigeria, where infrastructure challenges, such as poor road networks and limited railway access, can make the delivery of steel components difficult. Additionally, concrete's high durability and resistance to corrosion make it particularly suitable for Nigeria's diverse climate, from the humid coastal regions to the arid northern landscapes, where extreme weather conditions can affect the longevity of wind energy structures.[232] With Nigeria's abundant limestone reserves in states like Ogun, Benue, and Kogi, the raw materials for cement production—an essential component of concrete—are readily available,[233] further strengthening the case for increased local use of concrete wind turbine towers. Major cement and limestone processing companies such as Dangote Cement, Lafarge Africa, and BUA Cement are well-positioned to support the large-scale production of concrete components for wind energy infrastructure, reducing import dependence and lowering costs for domestic RE projects.

However, while concrete offers advantages in cost reduction and local availability, it also presents significant challenges that must be addressed. One major drawback is the additional weight of concrete structures compared to steel, which can complicate foundation requirements and increase installation time.[234] Furthermore, while concrete is durable, it lacks the flexibility of steel, making it more vulnerable to cracking under repeated stress, especially in areas with fluctuating wind speeds.[235] Research into high-performance concrete blends, such as fiber-reinforced or prestressed concrete,[236–238] could help mitigate these issues and enhance the longevity of wind turbine towers in Nigeria. Additionally, large-scale adoption of concrete for wind energy infrastructure would require substantial investment in specialized construction techniques and workforce training to ensure quality control and structural integrity.[236–238] With strategic planning, government incentives, and collaboration between the energy and construction sectors, concrete could serve as a sustainable, cost-effective material for expanding Nigeria's wind energy capacity.

These materials collectively support the effective operation of wind turbines in Nigeria, contributing to the country's RE landscape despite the challenges posed by infrastructure, material costs, and sourcing limitations.

5.3 Biomass

Biomass energy technologies in Nigeria utilize a range of materials to convert organic matter into heat, electricity, or biofuels, leveraging the country's abundant agricultural and forestry resources.[239] The key materials used in biomass energy production include:

5.3.1 Agricultural residues. Agricultural residues refer to organic materials generated as by-products during crop cultivation and processing.[240] These residues fall into two main categories: crop residues, which remain on farmlands post-harvest, and agro-industrial by-products, which result from processing agricultural commodities.[241,242] Crop residues, often discarded or incinerated before the next planting season, are considered primary or field-based residues, whereas those formed during processing are classified as secondary or process-based residues.[243,244] Both types hold significant potential for energy generation, yet they remain largely underutilized. In many cases, these residues are repurposed as livestock feed, natural fertilizers, or erosion control measures, but a substantial portion—estimated at nearly half—is burned on farmland before the next planting cycle, leading to environmental concerns and loss of valuable biomass.[240,242–244]

The characteristics of agricultural residues, such as density, moisture content, and particle size, are influenced by factors including crop type, harvest stage, and storage conditions.[245] These variations determine their suitability for different applications, particularly in bioenergy production. In Nigeria, a vast amount of residues from staple crops like cassava, maize, rice, palm kernel, and sugarcane are readily available and can contribute significantly to the country's RE sector (see Table 4).[246,248,250,252,254,256] For example, according to research, cassava peels alone, with a calorific value ranging from 15.22 to

Table 4 Biomass residue availability and energy potential from agricultural crops in Nigeria

Crop	Residue type	Crop production (million tons per year)	Estimated residue production (million tons per year)	Residue-to-product ratio (RPR)	Calorific value (MJ kg^{-1})	Potential energy yield (PJ per year)	References
Rice	Husk	8.5	1.2	0.17–0.35	12–16	20–120	243, 244, 246 and 247
Maize	Cob straw husk	11	>20	1.35–2.0	12–14	14–211	145, 247 and 248
Cassava	Peels	>70	>15.3	0.2–0.91	15.22–19	173	249 and 250
Yam	Peels	61.2	>3.8	0.2–1	5.8–13.8	106.9	251 and 252
Sorghum	Stalk, husk	6.9	2–3	0.3–1	18.2	88–89	253 and 254
Millet	Straw	2	0.8	0.4–0.75	15.27	90	255 and 256
Sugarcane	Bagasse, leaves	2.4	0.72	0.33	16–18	1–2.5	257
Groundnut	Shells, straw	3.3–4.45	1.7–5.34	0.37–1.2	18–27	30.31–77	258 and 259
Oil palm	Fronds, shells, fibre	1.2	>1	0.8–1.0	20.3–39	200–300	260
Cocoa	Pod, husk	0.27	0.681	1.0–2.0	15–18	55.4	261–263
Cowpea	Shell	3.6		1.2–1.9	14–16	97.61	264

19 MJ kg^{-1}, have an estimated energy yield of 173 PJ per year,[257] making it one of the most promising biomass resources in Nigeria.[265] Similarly, oil palm residues, including fronds, shells, and fibre, have an impressive energy yield of 200–300 PJ per year, largely untapped for large-scale bioenergy production.[266] Groundnut shells and straw, with calorific values ranging from 18 to 27 MJ kg^{-1}, could generate up to 77 PJ per year, yet they remain mostly discarded as agricultural waste. Other valuable biomass sources, such as sorghum stalks (88–89 PJ per year), millet straw (90 PJ per year), and cocoa pod husks (55.4 PJ per year), further highlight Nigeria's immense bioenergy potential.[58] With Nigeria's growing demand for energy and ongoing power supply challenges, leveraging these agricultural residues for biomass energy production could significantly reduce fossil fuel dependence, enhance rural electrification, and create new economic opportunities for farmers.

Despite this potential, Nigeria's biomass energy sector remains largely undeveloped due to weak policy support, limited investment, and inefficient conversion technologies. Unlike countries such as Germany, Brazil and Thailand, which have successfully integrated agricultural waste into their national energy mix,[267,268] Nigeria continues to rely heavily on traditional biomass use, such as firewood and inefficient charcoal production. Expanding R&D into biomass conversion technologies, such as anaerobic digestion for biogas, pyrolysis for bio-oil, and direct combustion for electricity generation, would help maximize the energy potential of these residues. Additionally, establishing government-backed incentives and financing schemes for smallholder farmers and agro-processing industries to invest in bioenergy solutions could accelerate adoption. Public-private partnerships (PPPs) could also facilitate the development of biomass-to-power plants, producing cleaner and more affordable electricity for rural communities.

Relying on unconventional feedstocks like straws, stalks, and bagasse for biofuel production offers the significant benefit of preserving food supplies, as only agricultural residues are utilized rather than edible crops.[268] Regardless of the specific biorefining methods employed, certain byproducts will inevitably emerge that are challenging to repurpose into high-value biofuels or biomaterials. These residual biomass materials often consist of lignin fragments, unconverted carbohydrates, and other organic compounds that must be managed responsibly to minimize environmental impact.[246] Given their inherent chemical energy, these waste materials serve as valuable inputs for biorefineries and are particularly well-suited for thermochemical processes that convert them into syngas, further enhancing the efficiency and sustainability of biofuel production.

5.3.2 **Forestry waste.** Forest biomass is broadly classified into two main categories: above-ground and below-ground biomass.[269] The above-ground component includes all living organic material found above the soil surface, such as tree bark, branches, leaves, seeds, stems, and stumps. In Nigeria, a significant concentration of this woody biomass is located in the Niger Delta, which coincidentally is also home to the country's major petroleum refineries.[270] On the other hand, below-ground biomass consists of all living root systems,

Table 5 Annual production and consumption of forest resources in Nigeria

Forest resource	Annual production (million m^3)	Annual consumption (million m^3)	References
Fuelwood & charcoal	66.2	66.2	277
Sawn timber	2.0	2.0	278
Pulpwood	0.12	0.12	279
Non-timber forest products (NTFPs)	No complete list	—	279

although finer roots measuring less than 2 mm in diameter are often excluded due to their close association with soil organic matter and litter, making them difficult to distinguish.[271]

As a key source of renewable raw materials, forest biomass holds considerable potential for strengthening Nigeria's biofuel industry. The Global Forest Resources Assessment (FRA) provides insight into the country's forest biomass reserves, demonstrating the scale at which these resources can be utilized.[272] The forest sector presents significant opportunities for industrial applications, particularly in RE production and fiber supply.[273] Industries leveraging forest-based resources can drive economic development by investing in bio-refineries that produce liquid biofuels and other biomaterials.[274] This shift towards bio-based production enhances sustainability, reduces dependence on fossil fuels, and positions forest industries as key players in Nigeria's RE landscape.[272]

Governments worldwide are increasingly investing in biofuels and bioenergy, with a particular focus on the forestry sector due to its potential role in supporting a sustainable, low-carbon economy.[274] Many nations recognize the forest industry as a viable avenue for RE production, aligning with global efforts to transition toward a green economy. For instance, Canada's 'Bio-Pathways' initiative has been instrumental in exploring new opportunities for the forest sector to enter the bioeconomy. This project, initiated in 2009, aimed to identify sustainable ways for the forest industry to produce a range of new products from wood fiber.[275] The country is now focusing on utilizing high-value sawn wood and other wood-based products to transform existing mills into bio-refineries.[276] These modern facilities aim to produce bioenergy, specialized chemicals, and advanced fiber materials, shifting the industry toward sustainability and higher-value outputs.

At present, forests, communal farmlands, and private agricultural lands serve as the country's primary sources of fuelwood. Wood-based biomass, particularly in the form of firewood and charcoal, remains the dominant source of household energy.[272] It is estimated that in 2019 alone, Nigeria produced and consumed over 66.2 million cubic meters of fuelwood,[277] underscoring the critical role of forest biomass in the nation's energy mix (see Table 5). Given that approximately 55% of global wood consumption in developing countries is attributed to fuelwood use,[280] Nigeria's reliance on forest-derived biomass highlights both the necessity for improved management strategies and the potential for advancing bio-energy production on a larger scale.

Forest residues represent a largely underutilized source of biomass energy across many African nations.[281] These materials include by-products from wood processing industries, such as discarded wood scraps, sawmill by-products, and carpentry waste.[275] Specifically, they consist of materials like sawdust, veneer log cores, rejected slabs, trimmings, and wood edgings that are unsuitable for timber applications. Additionally, biodegradable green waste generated from forestry activities can be repurposed through conversion techniques such as gasification or hydrolysis, transforming these residues into useful biofuels.[276]

Similar to agricultural waste, forest residues are secondary products obtained from existing forestry operations, eliminating the need for additional land cultivation.[282] Their availability is directly linked to the productivity of the wood-processing industry. The characteristics of these residues—including typical energy content and moisture content (ranging from 12% to 55% on a dry basis)—are influenced by processing methods and the specific environmental conditions of the forests from which they originate (see Table 6).

5.3.3 Animal waste. Nigeria has a substantial potential for biogas production, with fresh animal waste serving as a valuable resource.[286–288] Estimates suggest that the country can

Table 6 Energy potential and conversion pathways of forest residues in Nigeria

Forest residue type	Source	Typical energy content (MJ kg^{-1})	Conversion potential	References
Sawdust	Sawmills, wood workshops	11–20	Biomass pellets, biochar, syngas	283
Wood chips	Timber processing, logging	12.5–19	Direct combustion, biofuel	284
Bark	Sawmills, furniture industry	15–23	Pyrolysis oil, heat energy	285
Veneer log cores	Plywood and veneer industries	14–23	Biomass briquettes, ethanol	284
Tree stumps and roots	Land clearing, logging waste	15–18	Biogas, syngas, charcoal	284
Forest floor biomass	Fallen branches, dead wood	12–16	Fuelwood, biochar production	284
Green waste	Tree pruning, forest clearing	10–15	Biogas, composting	284

Table 7 Biogas potential from animal waste in Nigeria

Animal type	Estimated population (millions)	Waste generation (kg per day per animal)	Total waste generated (t per day)	Biogas yield (m^3 per kg of waste)	Total biogas potential (million m^3 per day)	References
Cattle	16.0	25	225 000	0.03	1.6	286, 289 and 290
Goats	51.0	7.3	103 500	0.03	1.6	286, 289 and 290
Sheep	32.1	4	88 000	0.03	1.0	286, 289 and 290
Pigs	7.0	6	42 000	0.04	0.38	286, 289 and 290
Chickens	156.0	0.15	27 000	0.04	0.24	286, 289 and 290

generate approximately 6.8 million cubic meters of biogas daily, given that each kilogram of fresh animal waste yields around 0.03 cubic meters of gas.[289] With a daily production of about 227 500 tonnes of fresh animal waste, the energy reserves from livestock waste contribute significantly to the country's RE potential (see Table 7).[104,289] These organic residues, much like agricultural by-products, represent an underutilized resource that can be effectively harnessed to support sustainable energy initiatives. Livestock farming in Nigeria primarily involves cattle, pigs, goats, sheep, and poultry, all of which generate substantial waste suitable for biogas production.[286] Through anaerobic digestion, these organic materials can be converted into methane-rich biogas, offering an environmentally friendly alternative to fossil fuels.[291] The proper management and utilization of animal waste can not only reduce environmental pollution but provide a reliable energy source for rural and urban communities.

In Nigeria, livestock distribution varies significantly by region. Cattle, goats, and sheep are primarily raised in the northern states, where large-scale commercial farms house thousands of cattle.[292] In contrast, pig farming is more prevalent in the southern part of the country, while poultry production is widespread, particularly in the south, where many households—both urban and rural—keep a small number of birds alongside other livestock.[293] The regional differences in livestock farming are influenced by climate, cultural preferences, and available grazing land, shaping the country's agricultural and energy potential. Considering biogas production from animal waste, the northern region holds a greater potential due to its high concentration of cattle farms.[292] Cattle generate significant amounts of organic waste, which can be efficiently processed through anaerobic digestion to produce biogas.[294] This makes the north a more viable location for large-scale biogas initiatives, as the sheer volume of waste available provides a consistent and sustainable feedstock for energy production. By harnessing this resource, Nigeria can develop a decentralized RE system, reducing reliance on fossil fuels while addressing waste management challenges.

6 Current challenges of renewable energy usage in Nigeria

Despite government acknowledgment of RE as a valuable alternative to fossil fuels, the pace of RE development and implementation in Nigeria remains slow. Investment in RE deployment is strikingly low, especially when contrasted with the funding directed toward conventional electricity.[58] Additionally, the commitment to implementing existing policies and objectives, as outlined in policy documents, may not be progressing as quickly as anticipated. Addressing these challenges is essential for achieving widespread RE adoption. According to research, factors such as weak regulatory frameworks, limited RE training, high deployment costs, and a shortage of skilled workers have hindered the viability of RE technology in Nigeria. Below is a brief overview of some of these key challenges.

6.1 Ineffective policies

Given the challenging state of Nigeria's energy sector and the limited penetration of RE sources, the Energy Commission of Nigeria (ECN) has issued several policies aimed at enhancing energy production and promoting renewables. However, these policies have had limited success. Research indicates several reasons for this. For instance, Nigeria's energy policies have historically favored centralized generation and conventional fossil fuel power sources. Current subsidies and incentives that support grid-based fossil fuel energy discourage investments in renewable alternatives, stalling their growth. Furthermore, high regulatory risks have dampened RE investments, as decentralized renewable power lacks assured grid connectivity, a key consideration for financial institutions and potential investors.[171]

6.2 Poor funding

Securing funding for RE initiatives often has a low success rate. Many financial institutions consider RE projects high-risk and therefore prefer to lend for fossil fuel power plant development, which is viewed as more stable. RE technologies such as solar, electric vehicles, and biofuel plants are often deemed too immature for substantial investment. Consequently, banks tend to charge higher interest rates and limit long-term loans, seeing RE financing as risky. Despite government policies allowing independent power producers to generate electricity, these financing challenges could hinder RE growth in Nigeria. Furthermore, the high cost of RE technology makes it unaffordable for many Nigerians and rural communities to install their own RE systems without financial support.[129]

6.3 Limited awareness

About 200 million people live in Nigeria, and the great majority of them are unaware of the potential RE resources that might be readily used to satisfy their energy demands. Approximately 60% of this population does not have access to power and lives in isolated, rural locations. Because of its poor acceptability, RE technologies are not widely used, and the market views investing in RE as a high-risk venture.[118] In Nigeria, despite their significant CO_2 emissions, diesel and gasoline generators are still widely used to generate energy, with very few private residences and business establishments now using RE technology. This is a result of a lack of knowledge about the advantages of inexpensive RE technology over generators that rely on fossil fuels. Improving the local population's access to knowledge about relevant RE technology will boost RE adoption and support climate change mitigation initiatives.[82]

6.4 High cost of renewable energy implementation

Deploying RE technology often involves significant upfront investment. The high cost of RE-generated power reflects this initial expense, which may make it a less attractive option for the Nigerian government compared to conventional energy sources. Additionally, Nigeria lacks a robust domestic manufacturing capacity for key RE components. For instance, there is minimal capacity for producing solar PV and small hydro power (SHP) components, and virtually none for other RE systems.[83] Consequently, many RE-related components must be imported, which introduces supply chain challenges, such as extended project timelines, high import taxes, delays in customs clearance, and increased costs this trend is gradually improving as solar module manufacturing equipment enters Nigeria, and RE component costs decline in international markets.[232]

6.5 Limited skilled workforce

Nigeria currently faces a shortage of skilled labor needed to manage the challenges of energy supply and demand. The success of any RE project relies on having trained local experts for maintenance and support.[84] One of the primary reasons for the inefficiency of RE technologies has been the insufficient transfer of technical skills to local users. To ensure consistent maintenance of RE systems, more Nigerians—particularly in rural areas—need training in the relevant technical skills for RE deployment. Various energy research centers and reports have highlighted efforts to prepare a skilled workforce for the RE sector.[211]

7 Future opportunities

For any meaningful progress in mitigating climate change, Nigeria should rejig its energy mix. The share of RE in the economy should be increased to surpass that of conventional energy sources. The following should be considered:

7.1 Material innovation

Material innovation presents a promising opportunity for advancing RE technology in Nigeria, particularly by promoting research into alternative materials such as organic photovoltaics (OPVs) and locally sourced biomass for energy storage. Organic PV, made from carbon-based molecules or polymers, offer an adaptable, lightweight, and potentially less expensive alternative to traditional silicon-based solar cells. With Nigeria's abundant sunlight and organic materials, OPVs could be developed using locally sourced resources, reducing the dependency on costly imports.[85] This shift towards organic materials not only aligns with the global push for more sustainable, environmentally friendly energy solutions but also opens the door for Nigeria to become a leader in tropical PV innovation. Furthermore, increased investment in OPV research could stimulate local industries, create jobs, and encourage collaborative efforts between universities, research institutions, and industry stakeholders.[86]

For Nigeria to capitalize on material innovation in RE, it is recommended to invest in R&D of alternative materials, particularly organic PVs and biomass-derived energy storage solutions. Establishing partnerships between universities, local industries, and international research institutions can accelerate the development of locally sourced, cost-effective materials, reducing reliance on imports and fostering a sustainable supply chain.[87] Government incentives, such as grants and tax relief for research on renewable materials, would encourage private sector involvement, while training programs in material science and engineering can build a skilled workforce to support this sector. By prioritizing these initiatives, Nigeria can develop unique, locally adapted RE technologies that bolster energy independence and support long-term economic growth.[127]

7.2 Adjust RE policies

By effectively adjusting its RE policies, the Nigerian government can draw insights from other economies where RE has been successfully implemented. To encourage more private investment in the country's RE sector, appropriate incentives should be established. For instance, introducing a subsidy program that reduces the cost of RE installations for households would encourage families and businesses to adopt RE systems as backup solutions, replacing petroleum generators.[88] These subsidies could significantly improve rural electrification by enabling residents in remote areas to establish their own power sources. Notably, RE subsidies need not be permanent, especially if Nigeria increases local production of RE equipment. As domestic production and usage expand, costs are likely to decrease, making the sector self-sustaining. Currently, importation costs are a major contributor to high RE installation expenses. If Nigeria is committed to using RE for climate change mitigation, the government must prioritize establishing a local manufacturing base for RE technology.

7.3 Enhance access to credit facilities

To encourage RE adoption in Nigeria, access to financial facilities is crucial. Nigeria should seek low-interest financing for large RE projects from the World Bank and other international financial organizations. With the Paris Agreement emphasizing global action on climate change, wealthier nations should support the growth of RE in Africa and other developing regions.[89] Domestically, financial institutions should receive assurances from the Central Bank of Nigeria on the security of loans for RE ventures. Such assurances, along with access to affordable financing, would encourage individual purchases of RE installations and attract private investment. Educating the Nigerian public on the economic and environmental benefits of adopting RE is also essential. Raising awareness about reducing carbon and greenhouse gas emissions will enable people and businesses to make environmentally responsible energy choices.

7.4 Improve skilled workforce

To support a robust and sustainable RE system, skilled labor development is necessary. Efforts should be increased to equip Nigerians with the technical skills required for a RE-based economy. Given the complexity of RE, educating the public must go beyond traditional media, integrating a curriculum that reflects societal needs. Enhancing the integration of sustainable development principles in national science and technology education and policy is also vital; sustainability should be a key element of energy education to foster a culture of sustainable energy use among Nigerians.

To spread knowledge and raise awareness about RE effectively, a multi-channel approach is recommended. Alongside educational institutions, various media outlets, conferences, public lectures, community forums, and science and technology exhibitions should be utilized to reach a broader audience and emphasize the benefits of RE over traditional energy sources.

8 Conclusion

As Nigeria strives towards sustainable energy independence, the integration of RE is paramount to achieving long-term economic resilience and environmental protection. With abundant natural resources, such as solar, wind, biomass, and hydropower, Nigeria has the potential to transition from a fossil fuel-dependent economy to a diversified and sustainable energy system. This shift is not merely an environmental necessity but a strategic imperative for national security, economic stability, and rural development. By leveraging its RE resources, Nigeria can reduce carbon emissions, minimize reliance on fossil fuel imports, and mitigate the economic vulnerabilities associated with fluctuating global oil prices. Furthermore, expanding RE adoption will enhance energy security, create employment opportunities, and foster industrial growth, positioning Nigeria as a leader in sustainable energy in Africa.

However, realizing this vision requires decisive action across multiple sectors, with a comprehensive strategy that addresses the systemic challenges hindering RE development. First, policy reform must prioritize a long-term regulatory framework that encourages private sector investment in RE infrastructure. The Nigerian government should establish legally binding RE procurement targets, streamline licensing processes for independent power producers (IPPs), and introduce robust incentives—such as tax breaks, feed-in tariffs, and risk guarantees—to attract both local and foreign investment. Moreover, integrating RE policies with Nigeria's broader industrialization and economic diversification agenda will ensure a more cohesive energy transition strategy. Second, investment in R&D is crucial to fostering local innovation in RE materials and technologies. Nigeria's reliance on imported solar panels, wind turbines, and battery storage systems inflates project costs and limits scalability. By supporting material science research and indigenous production of RE components—such as silicon for solar cells, bio-based energy storage, and lightweight wind turbine materials—Nigeria can reduce dependency on expensive imports and develop cost-effective, climate-resilient solutions tailored to its unique energy landscape. Strengthening partnerships between Nigerian universities, research institutions, and international organizations will facilitate knowledge transfer and accelerate breakthroughs in RE efficiency and affordability. Third, financial accessibility must be improved to support RE adoption at both the commercial and grassroots levels. The establishment of a dedicated RE Investment Fund, backed by government guarantees and international climate finance, can provide low-interest loans and grants for RE startups, rural electrification projects, and off-grid solutions. Additionally, financial institutions should introduce flexible financing models—such as pay-as-you-go solar schemes and micro-credit loans—to enable low-income households and small businesses to transition to RE without prohibitive upfront costs.

Equally important is public engagement and education, which will play a critical role in fostering a cultural shift towards sustainable energy adoption. Many Nigerians remain unaware of the economic and environmental benefits of RE, leading to slow uptake despite increasing energy insecurity. Large-scale public awareness campaigns, integration of RE education into academic curricula, and training programs for RE technicians and entrepreneurs will not only drive demand but also build a skilled workforce capable of sustaining Nigeria's clean energy sector. Community-driven RE projects should also be promoted to enhance local ownership and participation, ensuring that rural and underserved populations benefit equitably from Nigeria's energy transition.

The urgency of Nigeria's energy transition cannot be overstated. With a rapidly growing population and rising energy demand, delays in RE adoption will exacerbate economic stagnation, deepen energy poverty, and heighten environmental risks. The time for incremental progress is over—Nigeria must embrace bold, transformative action to accelerate its RE transition. Policymakers, researchers, industry leaders, and civil society must collaborate to implement targeted policies, drive innovation, and unlock financial mechanisms that will make RE viable and scalable. By taking these steps, Nigeria can move decisively toward a future where RE powers industries, electrifies rural communities, and safeguards natural resources for generations to come. The opportunity to lead Africa's energy revolution is within reach—what is needed now is the political will, strategic investment, and collective commitment to make this vision a reality.

Data availability

All data supporting the findings in this review paper are publicly available and can be accessed through the cited literature. The authors confirm that the data supporting the findings of this study are available within the article.

Conflicts of interest

There are no conflicts of interest to declare.

Acknowledgements

The author acknowledges the University of Nigeria Nsukka.

References

1 Z. Q. S. Nwokediegwu, K. I. Ibekwe, V. I. Ilojianya, E. A. Etukudoh and O. B. Ayorinde, Renewable energy technologies in engineering: a review of current developments and future prospects, *Eng. Sci. Technol.*, 2024, **5**(2), 367–384.

2 P. Jiang, Y. Van Fan and J. J. Klemeš, Impacts of COVID-19 on energy demand and consumption: challenges, lessons and emerging opportunities, *Appl. Energy*, 2021, **285**, 116441.

3 H. Jie, I. Khan, M. Alharthi, M. W. Zafar and A. Saeed, Sustainable energy policy, socio-economic development, and ecological footprint: the economic significance of natural resources, population growth, and industrial development, *Util. Policy*, 2023, **81**, 101490.

4 B. Gajdzik, R. Wolniak, R. Nagaj, B. Žuromskaitė-Nagaj and W. W. Grebski, The influence of the global energy crisis on energy efficiency: a comprehensive analysis, *Energies*, 2024, **17**(4), 947.

5 O. A. Somoye, Energy crisis and renewable energy potentials in Nigeria: a review, *Renewable Sustainable Energy Rev.*, 2023, **188**, 113794.

6 Q. Guo, S. Abbas, H. K. AbdulKareem, M. S. Shuaibu, K. Khudoykulov and T. Saha, Devising strategies for sustainable development in sub-Saharan Africa: the roles of renewable, non-renewable energy, and natural resources, *Energy*, 2023, **284**, 128713.

7 D. Akinyele, T. Ajewole, O. Olabode and I. Okakwu, Overview and comparative application of on-grid and off-grid renewable energy systems in modern-day electrical power technology, in *Adaptive Power Quality for Power Management Units Using Smart Technologies*, CRC Press, 2023, pp. 25–65.

8 E. Dinneya-Onuoha, V. S. Aigbodion and A. Ogbodo Agbo, Unlocking the optimization of electrical properties of epoxy-carbon nanotube composites modified with waste eggshell particles *via* the Taguchi-Grey method, *Oxford Open Mater. Sci.*, 2024, **4**(1), itae015.

9 S. Baurzhan and G. P. Jenkins, On-grid solar PV *versus* diesel electricity generation in sub-Saharan Africa: economics and GHG emissions, *Sustainability*, 2017, **9**(3), 372.

10 C. G. Monyei, A. O. Adewumi, M. O. Obolo and B. Sajou, Nigeria's energy poverty: insights and implications for smart policies and framework towards a smart Nigeria electricity network, *Renewable Sustainable Energy Rev.*, 2018, **81**, 1582–1601.

11 M. Amir and S. Z. Khan, Assessment of renewable energy: status, challenges, COVID-19 impacts, opportunities, and sustainable energy solutions in Africa, *Energy Built Environ.*, 2022, **3**(3), 348–362.

12 I. Adedeji, G. Deveci, H. Salman and I. Abiola, The benefits of solar energy on the provision of sustainable affordable housing in Nigeria, *J. Power Energy Eng.*, 2023, **11**(6), 1–15.

13 R. Cassia, M. Nocioni, N. Correa-Aragunde and L. Lamattina, Climate change and the impact of greenhouse gasses: CO_2 and NO, friends and foes of plant oxidative stress, *Front. Plant Sci.*, 2018, **9**, 273.

14 Statista, Cumulative renewable energy capacity worldwide from 2010 to 2024, 2025, available from: **https://www.statista.com/statistics/1094331/global-renewable-capacity-cumulative/**.

15 Y. F. Nassar, H. J. El-Khozondar, A. A. Alatrash, B. A. Ahmed, R. S. Elzer, A. A. Ahmed and M. M. Khaleel, Assessing the

viability of solar and wind energy technologies in semi-arid and arid regions: a case study of Libya's climatic conditions, *Appl. Sol. Energy*, 2024, **60**(1), 149–170.

16 Y. F. Nassar, H. J. El-Khozondar, M. Elnaggar, F. F. El-batta, R. J. El-Khozondar and S. Y. Alsadi, Renewable energy potential in the State of Palestine: proposals for sustainability, *Renew. Energ*, 2024, **49**, 100576.

17 Y. F. Nassar, H. J. El-Khozondar and M. A. Fakher, The role of hybrid renewable energy systems in covering power shortages in public electricity grid: an economic, environmental and technical optimization analysis, *J. Energy Storage*, 2025, **108**, 115224.

18 Statista, Total renewable energy capacity in Africa from 2012 to 2023, 2025b, available from: https://www.statista.com/statistics/1277944/total-renewable-energy-capacity-in-africa/.

19 P. Onuh, J. O. Ejiga, E. O. Abah, J. O. Onuh, C. Idogho and J. Omale, Challenges and opportunities in Nigeria's renewable energy policy and legislation, *World J. Adv. Res. Rev.*, 2024, **23**(2), 2354–2372.

20 A. Giwa, A. Alabi, A. Yusuf and T. Olukan, A comprehensive review on biomass and solar energy for sustainable energy generation in Nigeria, *Renewable Sustainable Energy Rev.*, 2017, **69**, 620–641.

21 Y. N. Chanchangi, F. Adu, A. Ghosh, S. Sundaram and T. K. Mallick, Nigeria's energy review: focusing on solar energy potential and penetration, *Environ. Dev. Sustain.*, 2023, **25**(7), 5755–5796.

22 C. Ogbonnaya, C. Abeykoon, U. M. Damo and A. Turan, The current and emerging renewable energy technologies for power generation in Nigeria: a review, *Therm. Sci. Eng. Prog.*, 2019, **13**, 100390.

23 J. Nchege and C. Okpalaoka, Hydroelectric production and energy consumption in Nigeria: problems and solutions, *Renewable Energy*, 2023, **219**, 119548.

24 Statista, Hydropower capacity in Nigeria 2011–2023, 2024, available from: https://www.statista.com/statistics/1278094/hydropower-capacity-in-nigeria/.

25 K. R. Shivanna, Climate change and its impact on biodiversity and human welfare, *PINSA-A:Proc. Indian Natl. Sci. Acad., Part A*, 2022, **88**, 160, DOI: 10.1007/S43538-022-00073-6.

26 F. Bibi and A. Rahman, An overview of climate change impacts on agriculture and their mitigation strategies, *Agriculture*, 2023, **13**, 1508, DOI: 10.3390/AGRICULTURE13081508/S1.

27 Z. A. Elum and A. S. Momodu, Climate change mitigation and renewable energy for sustainable development in Nigeria: a discourse approach, *Renewable Sustainable Energy Rev.*, 2017, **76**, 72.

28 M. A. Adeshina, A. M. Ogunleye, H. O. Suleiman, A. O. Yakub, N. N. Same, Z. A. Suleiman and J. S. Huh, From potential to power: advancing Nigeria's energy sector through renewable integration and policy reform, *Sustainability*, 2024, **16**(20), 8803.

29 O. N. Richard and O. Eseosa, Evaluation of wind energy potentials in some selected areas in the six geo-political regions in Nigeria, *J. Altern. Renew. Energy Sources*, 2022, **8**(1), 20–37.

30 C. Ezekwem and S. Muthusamy, Feasibility study of integrating the renewable energy system for increased electricity access: a case study of Choba community in Nigeria, *Sci. Afr.*, 2023, **21**, e01781.

31 S. Boadu and E. Otoo, A comprehensive review on wind energy in Africa: challenges, benefits and recommendations, *Renewable Sustainable Energy Rev.*, 2024, **191**, 114035.

32 International Renewable Energy Agency (IRENA), Nigeria, 2024, available from: https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/Africa/Nigeria_Africa_RE_SP.pdf.

33 C. Ezekwem, S. Muthusamy and P. C. Ezekwem, Optimal selection and design of grid-connected hybrid renewable energy system in three selected communities of Rivers State, *Sci. Afr.*, 2024, **25**, e02305.

34 M. J. B. Kabeyi and O. A. Olanrewaju, Sustainable energy transition for renewable and low carbon grid electricity generation and supply, *Front. Energy Res.*, 2022, **9**, 743114.

35 V. S. Aigbodion and E. Dinneya-Onuoha, Unveiling the anti-corrosion properties of Zn-eggshell particle composite coatings on mild steel in seawater-simulated solution using starch as a modifier, *RSC Adv.*, 2024, **14**, 24548–24560.

36 S. Yana, M. Nizar and D. Mulyati, Biomass waste as a renewable energy in developing bio-based economies in Indonesia: A review, *Renewable Sustainable Energy Rev.*, 2022, **160**, 112268.

37 N. Keena, M. Raugei, M. L. Lokko, M. A. Etman, V. Achnani, B. K. Reck and A. Dyson, A life-cycle approach to investigate the potential of novel biobased construction materials toward a circular built environment, *Energies*, 2022, **15**(19), 7239.

38 F. Envall and H. Rohracher, Technopolitics of future-making: The ambiguous role of energy communities in shaping energy system change, *Environ. Plan. E: Nat. Space*, 2024, **7**(2), 765–787.

39 Z. Zhangqi, C. Zhuli and H. Lingyun, Technological innovation, industrial structural change and carbon emission transferring *via* trade—An agent-based modeling approach, *Technovation*, 2022, **110**, 102350.

40 O. J. Olujobi, U. E. Okorie, E. S. Olarinde and A. D. Aina-Pelemo, Legal responses to energy security and sustainability in Nigeria's power sector amidst fossil fuel disruptions and low carbon energy transition, *Heliyon*, 2023, **9**(7), e17912.

41 A. S. Okoh and E. Okpanachi, Transcending energy transition complexities in building a carbon-neutral economy: The case of Nigeria, *J. Clean Energy Syst.*, 2023, **6**, 100069.

42 E. Barazza and N. Strachan, The key role of historic path-dependency and competitor imitation on the electricity sector low-carbon transition, *Energy Strategy Rev.*, 2021, **33**, 100588.

43 J. Niskanen, S. Haikola, D. Magnusson and J. Anshelm, Swedish wind power expansion: Conflicting

responsibilities between state and municipalities, *Renewable Sustainable Energy Rev.*, 2024, **206**, 114881.

44 T. M. Archana, T. K. Neelima and L. Thomas, Biomass Derived Solar-Thermal Materials, in *Handbook of Advanced Biomass Materials for Environmental Remediation*, Springer Nature Singapore, Singapore, 2024, pp. 273–290.

45 J. O. Unuofin, S. A. Iwarere and M. O. Daramola, Embracing the future of circular bio-enabled economy: unveiling the prospects of microbial fuel cells in achieving true sustainable energy, *Environ. Sci. Pollut. Res.*, 2023, **30**(39), 90547–90573.

46 O. A. Adelekan, B. S. Ilugbusi, O. Adisa, O. C. Obi, K. F. Awonuga, O. F. Asuzu and N. L. Ndubuisi, Energy transition policies: a global review of shifts towards renewable sources, *Eng. Sci. Technol.*, 2024, **5**(2), 272–287.

47 N. C. Nwankwo, S. Madougou, M. M. Inoussa, E. Okonkwo and N. S. A. Derkyi, Review of Nigeria's renewable energy policies with focus on biogas technology penetration and adoption, *Discover Energy*, 2024, **4**(1), 14.

48 G. Omoaka, Renewable Energy Disputes and Arbitration in West Africa: Nigeria, The Case Study, in *The Palgrave Handbook of Arbitration in the African Energy and Mining Sectors*, Springer Nature Switzerland, Cham, 2024, pp. 1–25.

49 C. O. Nwachukwu, E. O. Diemuodeke, T. A. Briggs, M. M. Ojapah, C. Okereke, K. E. Okedu and A. Kalam, Low/zero carbon technology diffusion and mapping for Nigeria's decarbonization, *Int. J. Sustainable Energy*, 2024, **43**(1), 2317146.

50 L. Kanger, Rethinking the Multi-level Perspective for energy transitions: From regime life-cycle to explanatory typology of transition pathways, *Energy Res. Soc. Sci.*, 2021, **71**, 101829.

51 O. O. Babayomi, B. Olubayo, I. H. Denwigwe, T. E. Somefun, O. S. Adedoja, C. T. Somefun and A. Attah, A review of renewable off-grid mini-grids in Sub-Saharan Africa, *Front. Energy Res.*, 2023, **10**, 1089025.

52 A. O. Cyril, C. O. Ujah, B. N. Ekwueme and C. O. Asadu, Photovoltaic mini-grid incorporation: The panacea for electricity crisis in sub-Saharan Africa, *Unconv. Resour.*, 2024, 100079.

53 O. V. Nwadiaru, T. Kukeera and D. Ebanehita, Enabling solar photovoltaics penetration in highly dependent African fossil fuel markets, in *Sustainable Fuel Technologies Handbook*, Academic Press, 2021, pp. 173–198.

54 M. Dhali, S. Hassan and U. Subramaniam, Comparative analysis of oil and gas legal frameworks in Bangladesh and Nigeria: a pathway towards achieving sustainable energy through policy, *Sustainability*, 2023, **15**(21), 15228.

55 F. Adeniyi and A. Isah, Unlocking renewables amid rentierism: Market constraints to Nigeria's energy transition, *Energy Res. Soc. Sci.*, 2023, **104**, 103248.

56 P. Newell, R. Price and F. Daley, Landscapes of (in) justice: Reflecting on voices, spaces and alliances for just transitions, *Energy Res. Soc. Sci.*, 2024, **116**, 103701.

57 C. G. Ozoegwu and P. U. Akpan, 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 Sustainable Energy Rev.*, 2021, **143**, 110887.

58 D. O. Obada, M. Muhammad, S. B. Tajiri, M. O. Kekung, S. A. Abolade, S. B. Akinpelu and A. Akande, A review of renewable energy resources in Nigeria for climate change mitigation, *Case Stud. Chem. Environ. Eng.*, 2024, **9**, 100669.

59 M. A. Adeshina, A. M. Ogunleye, H. O. Suleiman, A. O. Yakub, N. N. Same, Z. A. Suleiman and J. S. Huh, From potential to power: Advancing Nigeria's energy sector through renewable integration and policy reform, *Sustainability*, 2024, **16**(20), 8803.

60 M. J. Hilili, S. S. Akadiri and C. N. Eneanya, Powering Nigeria's future: balancing renewable and non-renewable energy for environmental sustainability, *Energy Syst.*, 2024, 1–22.

61 M. Shaaban and J. O. Petinrin, Renewable energy potentials in Nigeria: Meeting rural energy needs, *Renewable Sustainable Energy Rev.*, 2014, **29**, 72–84.

62 International Trade Administration (ITA), Electricity, Power Systems and Renewable Energy, 2023, available from: **https://www.trade.gov/country-commercial-guides/electricity-power-systems-and-renewable-energy#:~:text=countryby2023.-,Hydro,MWJebbaprojectswererehabilitated**.

63 B. Ali, N. Saadun, N. Kamarudin, M. A. Alias, N. M. Nawi and B. Azhar, Fuelwood value chain in Northern Nigeria: economic, environment, and social sustainability concerns, *Forests*, 2023, **14**(5), 906.

64 F. O. Olanrewaju, G. E. Andrews, H. Li and H. N. Phylaktou, Bioenergy potential in Nigeria, *Chem. Eng. Trans.*, 2019, **74**, 61–66.

65 Y. Umar, R. O. Yakubu, A. A. Abdulazeez and M. W. Ijeoma, Exploring Nigeria's waste-to-energy potential: a sustainable solution for electricity generation, *Clean Energy*, 2024, **8**(6), 82–95.

66 T. K. Yuguda, S. A. Imanche, T. Ze, T. Y. Akintunde and B. S. Luka, Hydropower development, policy and partnership in the 21st century: A China-Nigeria outlook, *Energy Environ.*, 2023, **34**(4), 1170–1204.

67 H. A. Ibrahim and M. K. Ayomoh, Optimum predictive modelling for a sustainable power supply mix: A case of the Nigerian power system, *Energy Strat. Rev.*, 2022, **44**, 100962.

68 G. K. Akporhonor, S. O. Otuagoma and T. A. Akporhonor, Nigerian wind energy status, *J. Wind Eng.*, 2024, **48**(2), 310–322.

69 A. A. Attabo, O. O. Ajayi, S. O. Oyedepo and S. A. Afolalu, Assessment of the wind energy potential and economic viability of selected sites along Nigeria's coastal and offshore locations, *Front. Energy Res.*, 2023, **11**, 1186095.

70 M. S. Adaramola and O. M. Oyewola, On wind speed pattern and energy potential in Nigeria, *Energy Policy*, 2011, **39**(5), 2501–2506.

71 U. C. Ben, A. E. Akpan, C. C. Mbonu and C. H. Ufuafuonye, Integrated technical analysis of wind speed data for wind energy potential assessment in parts of southern and central Nigeria, *Clean. Eng. Technol.*, 2021, **2**, 100049.

72 K. Owebor, E. O. Diemuodeke, T. A. Briggs and M. Imran, Power situation and renewable energy potentials in Nigeria–A case for integrated multi-generation technology, *Renewable Energy*, 2021, **177**, 773–796.
73 A. S. Aliyu, J. O. Dada and I. K. Adam, Current status and future prospects of renewable energy in Nigeria, *Renewable Sustainable Energy Rev.*, 2015, **48**, 336–346.
74 Y. S. Mohammed, M. W. N. Mustafa, N. Bashir and A. S. Mokhtar, Renewable energy resources for distributed power generation in Nigeria: A review of the potential, *Renewable Sustainable Energy Rev.*, 2013, **22**, 257–268.
75 O. O. Ajayi, G. Mokryani and B. M. Edun, Sustainable energy for national climate change, food security and employment opportunities: Implications for Nigeria, *Fuel Commun.*, 2022, **10**, 100045.
76 O. S. Ohunakin, Energy utilization and renewable energy sources in Nigeria, *J. Eng. Appl. Sci.*, 2010, **5**(2), 171–177.
77 Y. F. Nassar, H. J. El-Khozondar, M. M. Khaleel, A. A. Ahmed, A. H. Alsharif, M. H. Elmnifi and I. Mangir, Design of reliable standalone utility-scale pumped hydroelectric storage powered by PV/Wind hybrid renewable system, *Energy Convers. Manage.*, 2024, **322**, 119173.
78 H. J. El-Khozondar, F. El-batta, R. J. El-Khozondar, Y. Nassar, M. Alramlawi and S. Alsadi, Standalone hybrid PV/wind/diesel-electric generator system for a COVID-19 quarantine center, Environ. Prog. Sustain, *Energy*, 2023, **42**(3), e14049.
79 M. Majid, Renewable energy for sustainable development in India: current status, future prospects, challenges, employment, and investment opportunities, *Energy Sustain. Soc.*, 2020, **10**(1), 1–36.
80 A. Gungah, N. V. Emodi and M. O. Dioha, Improving Nigeria's renewable energy policy design: A case study approach, *Energy Policy*, 2019, **130**, 89–100.
81 B. B. Adetokun and C. M. Muriithi, Impact of integrating large-scale DFIG-based wind energy conversion system on the voltage stability of weak national grids: A case study of the Nigerian power grid, *Energy Rep.*, 2021, **7**, 654–666.
82 S. S. Siwal, Q. Zhang, N. Devi, A. K. Saini, V. Saini, B. Pareek and V. K. Thakur, Recovery processes of sustainable energy using different biomass and wastes, *Renewable Sustainable Energy Rev.*, 2021, **150**, 111483.
83 I. M. Toplicean and A. D. Datcu, An overview on bioeconomy in agricultural sector, biomass production, recycling methods, and circular economy considerations, *Agric*, 2024, **14**(7), 1143.
84 S. Barot, Biomass and bioenergy: resources, conversion and application, in *Renew. Energy Sustain. Growth Assess.*, 2022, pp. 243–262.
85 D. Gayen, R. Chatterjee and S. Roy, A review on environmental impacts of renewable energy for sustainable development, *Int. J. Environ. Sci. Technol.*, 2024, **21**(5), 5285–5310.
86 L. Fan and D. Wang, Natural resource efficiency and green economy: Key takeaways on clean energy, globalization, and innovations in BRICS countries, *Resour. Policy*, 2024, **88**, 104382.
87 J. O. Dirisu, E. Y. Salawu, I. C. Ekpe, N. E. Udoye, O. E. Falodun, S. O. Oyedepo and S. A. Kale, Promoting the use of bioenergy in developing nations: a CDM route to sustainable development, *Front. Energy Res.*, 2024, **11**, 1184348.
88 J. Popp, S. Kovács, J. Oláh, Z. Divéki and E. Balázs, Bioeconomy: Biomass and biomass-based energy supply and demand, *New Biotechnol.*, 2021, **60**, 76–84.
89 M. Kevser, M. Tekbaş, M. Doğan and S. Koyluoglu, Nexus among biomass energy consumption, economic growth, and financial development: Evidence from selected 15 countries, *Energy Rep.*, 2022, **8**, 8372–8380.
90 A. H. Demirbas and I. Demirbas, Importance of rural bioenergy for developing countries, *Energy Convers. Manage.*, 2007, **48**(8), 2386–2398.
91 I. W. Oyeniran and W. A. Isola, Patterns and determinants of household cooking fuel choice in Nigeria, *Energy*, 2023, **278**, 127753.
92 S. A. Mehetre, N. L. Panwar, D. Sharma and H. Kumar, Improved biomass cookstoves for sustainable development: A review, *Renewable Sustainable Energy Rev.*, 2017, **73**, 672–687.
93 R. Ahmad, H. N. Ilyas, B. Li, M. Sultan, M. Amjad, M. Aleem and F. Riaz, Current challenges and future prospect of biomass cooking and heating stoves in Asian Countries, *Front. Energy Res.*, 2022, **10**, 880064.
94 A. Adewuyi, Challenges and prospects of renewable energy in Nigeria: A case of bioethanol and biodiesel production, *Energy Rep.*, 2020, **6**, 77–88.
95 S. Mathur, A. V. Umakanth, V. A. Tonapi, R. Sharma and M. K. Sharma, Sweet sorghum as biofuel feedstock: recent advances and available resources, *Biotechnol. Biofuels*, 2017, **10**, 1–19.
96 A. Giwa, A. Alabi, A. Yusuf and T. Olukan, A comprehensive review on biomass and solar energy for sustainable energy generation in Nigeria, *Renewable Sustainable Energy Rev.*, 2017, **69**, 620–641.
97 I. A. Cruz, L. R. S. Andrade, R. N. Bharagava, A. K. Nadda, M. Bilal, R. T. Figueiredo and L. F. R. Ferreira, Valorization of cassava residues for biogas production in Brazil based on the circular economy: An updated and comprehensive review, *Clean. Eng. Technol.*, 2021, **4**, 100196.
98 A. M. Nizzy and S. Kannan, A review on the conversion of cassava wastes into value-added products towards a sustainable environment, *Environ. Sci. Pollut. Res.*, 2022, **29**(46), 69223–69240.
99 S. Sivamani, A. P. Chandrasekaran, M. Balajii, M. Shanmugaprakash, A. Hosseini-Bandegharaei and R. Baskar, Evaluation of the potential of cassava-based residues for biofuels production, *Rev. Environ. Sci. Bio/Technol.*, 2018, **17**, 553–570.
100 J. Ben-Iwo, V. Manovic and P. Longhurst, Biomass resources and biofuels potential for the production of

transportation fuels in Nigeria, *Renewable Sustainable Energy Rev.*, 2016, **63**, 172–192.
101 P. A. Okoro, K. Chong and M. Röder, Bioenergy potential in Nigeria, how to advance knowledge and deployment to enable SDG 7, *Wiley Interdiscip. Rev.:Energy Environ.*, 2024, **13**(4), e531.
102 S. E. Hosseini and M. A. Wahid, Utilization of biogas released from palm oil mill effluent for power generation using self-preheated reactor, *Energy Convers. Manage.*, 2015, **105**, 957–966.
103 F. A. Aisien and E. T. Aisien, Biogas from cassava peels waste, *Detritus*, 2020, **10**, 100.
104 E. L. Odekanle, O. J. Odejobi, S. O. Dahunsi and F. A. Akeredolu, Potential for cleaner energy recovery and electricity generation from abattoir wastes in Nigeria, *Energy Rep.*, 2020, **6**, 1262–1267.
105 S. O. Jekayinfa and V. Scholz, Laboratory scale preparation of biogas from cassava tubers, cassava peels, and palm kernel oil residues,, *Energy Sources, Part A*, 2013, **35**(21), 2022–2032.
106 A. A. Sokan-Adeaga and G. R. Ana, A comprehensive review of biomass resources and biofuel production in Nigeria: potential and prospects, *Rev. Environ. Health*, 2015, **30**(3), 143–162.
107 O. U. Godfrey, Renewable Energy from Agricultural Waste: Biogas Potential for Sustainable Energy Generation in Nigeria's Rural Agricultural Communities, *J. Eng Res. Reports*, 2024, **26**(12), 341–367.
108 Y. S. Mohammed, N. Bashir and M. W. Mustafa, Overuse of wood-based bioenergy in selected sub-Saharan Africa countries: review of unconstructive challenges and suggestions, *J. Cleaner Prod.*, 2015, **96**, 501–519.
109 I. N. Medugu, M. R. Majid, F. Johar and I. S. Taiwo, Assessing the impact of Forestry II program on agricultural productivity in the Arid Zone of Nigeria: A case of Kano and Jigawa State, *Manag Environ Qual Int J.*, 2014, **25**(6), 783–801.
110 E. J. Isukuru, J. O. Opha, O. W. Isaiah, B. Orovwighose and S. S. Emmanuel, Nigeria's water crisis: Abundant water, polluted reality, Clean, *Water*, 2024, 100026.
111 O. Adeoti, Constraints on data collection implementation at the river basin level in Nigeria, *J. Hydrol. Reg. Stud.*, 2020, **32**, 100738.
112 P. O. Youdeowei, H. O. Nwankwoala and D. D. Desai, Dam structures and types in Nigeria: sustainability and effectiveness, *Water Conserv. Manag.*, 2019, **3**(1), 20–26.
113 The Federal Ministry of Power, Works and Housing, The Nigerian power sector investment and guidelines, 2016, available from: https://fmhud.gov.ng/themes/front_end_themes_01/images/download/15378184714037.pdf.
114 Statista, Renewable energy share in electricity capacity in Nigeria from 2011 to 2023, 2025c, available from: https://www.statista.com/statistics/1278245/renewable-energy-share-of-electricity-capacity-in-nigeria/.
115 A. O. Onokwai, I. P. Okokpujie, M. O. Ibiwoye, H. I. Owamah, G. C. Ayuba and J. O. Dirisu, Effect of thermal and flow properties on the performance of Jebba Hydro-Power Plant, Jebba, Nigeria, *Mater. Today: Proc.*, 2022, **65**, 2245–2253.
116 A. A. Bisu, T. G. Ahmed, U. S. Ahmad and A. D. Maiwada, A SWOT analysis approach for the development of photovoltaic (PV) energy in Northern Nigeria, Clean, *Energy Syst.*, 2024, 100128.
117 S. L. Akintola and K. A. Fakoya, Small-scale fisheries in the context of traditional post-harvest practice and the quest for food and nutritional security in Nigeria, *Agric. Food Secur.*, 2017, **6**, 1–17.
118 O. E. Olabode, T. O. Ajewole, I. K. Okakwu, A. S. Alayande and D. O. Akinyele, Hybrid power systems for off-grid locations: A comprehensive review of design technologies, applications and future trends, *Sci. Afr.*, 2021, **13**, e00884.
119 D. Akinyele, T. Ajewole, O. Olabode and I. Okakwu, Overview and comparative application of on-grid and off-grid renewable energy systems in modern-day electrical power technology, in *Adaptive Power Quality for Power Management Units Using Smart Technologies*, CRC Press, 2023, pp. 25–65.
120 J. O. Oladigbolu, M. A. Ramli and Y. A. Al-Turki, Feasibility study and comparative analysis of hybrid renewable power system for off-grid rural electrification in a typical remote village located in Nigeria, *IEEE Access*, 2020, **8**, 171643–171663.
121 C. G. Ozoegwu, C. A. Mgbemene and P. A. Ozor, The status of solar energy integration and policy in Nigeria, *Renewable Sustainable Energy Rev.*, 2017, **70**, 457–471.
122 Power Technology, Power plant profile: Kumbotso Solar PV Park, Nigeria, 2024, available from: https://www.power-technology.com/data-insights/power-plant-profile-kumbotso-solar-pv-park-nigeria/.
123 N. S. Ugwuanyi, I. O. Ozioko, U. U. Uma, O. A. Nwogu, N. C. Ugwuoke, A. O. Ekwue and N. Nwokocha, Enhancing renewable energy-grid integration by optimally placed FACTS devices: the Nigeria case study, *Sci. J. Energy Eng.*, 2024, **12**(2), 16–25.
124 Y. N. Chanchangi, F. Adu, A. Ghosh, S. Sundaram and T. K. Mallick, Nigeria's energy review: Focusing on solar energy potential and penetration, *Environ. Dev. Sustain.*, 2023, **25**(7), 5755–5796.
125 Nigerian Electricity Regulatory Commission (NERC), Consultation paper for the review of the transmission loss factor for the transmission company of Nigeria, 2024, available from: https://nerc.gov.ng/wp-content/uploads/2021/11/ConsultationPaperonTLF_MO12-11-2021edited.pdf.
126 A. O. Adelaja, Barriers to national renewable energy policy adoption: Insights from a case study of Nigeria, *Energy Strat. Rev.*, 2020, **30**, 100519.
127 A. A. Mas'ud, A. V. Wirba, F. Muhammad-Sukki, I. A. Mas'ud, A. B. Munir and N. M. Yunus, An assessment of renewable energy readiness in Africa: Case study of Nigeria and Cameroon, *Renewable Sustainable Energy Rev.*, 2015, **51**, 775–784.

128 A. A. Mas'ud, A. V. Wirba, F. Muhammad-Sukki, R. Albarracín, S. H. Abu-Bakar, A. B. Munir and N. A. Bani, A review on the recent progress made on solar photovoltaic in selected countries of sub-Saharan Africa, *Renewable Sustainable Energy Rev.*, 2016, **62**, 441–452.
129 L. Baker, New frontiers of electricity capital: energy access in sub-Saharan Africa, *New Pol. Econ.*, 2023, **28**(2), 206–222.
130 O. Ikwuegbu, U. J. Idem, Y. E. Tunde, I. Bamidele, N. G. Ikpeze and O. I. Ayokunle, An assessment of the impacts of shifting to renewable energy systems on policies and economics in Nigeria: a solution for achieving Sustainable Development Goal 7, in *2024 IEEE 5th Int. Conf. Electro-Comput. Technol. Humanit. (NIGERCON)*, IEEE, 2024, pp. 1–4.
131 F. Nwaiwu, 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 Sustain. Soc.*, 2021, **11**, 48.
132 K. T. Lawal, Law, policy, and the development of renewable energy for electricity: a case for a renewable energy law in Nigeria, *Int. J. Leg. Inf.*, 2021, **49**, 3–15.
133 M. U. Emezirinwune, I. A. Adejumobi, O. I. Adebisi and F. G. Akinboro, Synergizing hybrid renewable energy systems and sustainable agriculture for rural development in Nigeria, e-Prime Adv, *Electr. Eng. Electron. Energy*, 2024, **7**, 100492.
134 O. J. Olujobi, O. S. Irumekhai and A. D. Aina-Pelemo, Sustainable development and national integration: a catalyst for enhancing environmental law compliance in Nigeria, *J. Environ. Policy Law*, 2024, **54**, 27–41.
135 M. Buchy and S. Shakya, Understanding the gap between the gender equality and social inclusion policy and implementation in the energy sector: the case of Nepal, *Energy Sustainable Dev.*, 2023, **76**, 101297.
136 O. Babatunde, E. Buraimoh, O. Tinuoye, C. Ayegbusi, I. Davidson and D. E. Ighravwe, Electricity sector assessment in Nigeria: the post-liberation era, *Cogent Eng.*, 2023, **10**, 2157536.
137 A. A. Adebiyi and K. Moloi, Renewable energy source utilization progress in South Africa: a review, *Energies*, 2024, **17**, 3487.
138 I. K. Rotich, H. Chepkirui and P. K. Musyimi, Renewable energy status and uptake in Kenya, *Energy Strat. Rev.*, 2024, **54**, 101453.
139 EMBER, China | Energy Trends, 2024, available from: https://ember-energy.org/countries-and-regions/china/#:∼:text=In2023%2Ccleanpowermade,ofcleanpowerat13%25.
140 Statista, Contribution of renewable energy to the German energy mix from 2010 to 2023, 2025d, available from: https://www.statista.com/statistics/737664/energy-mix-renewable-energy-germany/.
141 Statista, Leading countries in installed renewable energy capacity worldwide in 2023, 2025e, available from: https://www.statista.com/statistics/267233/renewable-energy-capacity-worldwide-by-country/.
142 Statista, Investments in renewable energy worldwide in 2023, by region, 2025g, available from: https://www.statista.com/statistics/186923/new-investments-worldwide-in-sustainable-energy-by-region/#:∼:text=In2023%2Cthelargestregional,significantonaglobalscale.
143 Statista, Total renewable energy capacity in Africa in 2023, by selected country, 2025f, available from: https://www.statista.com/statistics/1278058/leading-countries-in-renewable-energy-capacity-in-africa/#:∼:text=SouthAfricahadthelargest,capacity%2Catroughly6.7gigawatts.
144 Climatescope, Kenya, 2024, available from: https://www.global-climatescope.org/markets/kenya.
145 Statista, Global corn production in 2024/2025, by country, 2025h, available from: https://www.statista.com/statistics/254292/global-corn-production-by-country/.
146 A. Isah, M. O. Dioha, R. Debnath, M. C. Abraham-Dukuma and H. M. Butu, Financing renewable energy: policy insights from Brazil and Nigeria, *Energy Sustain. Soc.*, 2023, **13**, 2.
147 M. S. Nkambule, A. N. Hasan and T. Shongwe, Analyzing the Economic Viability of Microgrid Solutions in the South African Market, *IEEE Access*, 2025, **13**, 29091–29121.
148 A. Sawhney, Striving towards a circular economy: climate policy and renewable energy in India, *Clean Technol. Environ. Policy*, 2021, **23**, 491–499.
149 S. W. Ndiritu and M. K. Engola, The effectiveness of feed-in-tariff policy in promoting power generation from renewable energy in Kenya, *Renewable Energy*, 2020, **161**, 593–605.
150 G. Shrimali, S. Srinivasan, S. Goel and D. Nelson, The effectiveness of federal renewable policies in India, *Renewable Sustainable Energy Rev.*, 2017, **70**, 538–550.
151 W. Ma and W. Wang, Evolution of renewable energy laws and policies in China, *Heliyon*, 2024, **10**(8), e29712.
152 C. Croonenbroeck and D. Hennecke, Does the German renewable energy act provide a fair incentive system for onshore wind power?—A simulation analysis, *Energy Policy*, 2020, **144**, 111663.
153 S. A. Qadir, H. Al-Motairi, F. Tahir and L. Al-Fagih, Incentives and strategies for financing the renewable energy transition: A review, *Energy Rep.*, 2021, **7**, 3590–3606.
154 O. T. Ibitoye, O. S. Agunbiade, T. W. Ilemobola, A. B. Oluwadare, P. C. Ofodu, K. O. Lawal and J. O. Dada, Nigeria Electricity Grid and the Potentials of Renewable Energy Integration: A Concise Review, *IEEE Int. Energy Conf.*, 2022, 1–4.
155 O. M. Akinbami, S. R. Oke and M. O. Bodunrin, The state of renewable energy development in South Africa: An overview, *Alexandria Eng. J.*, 2021, **60**(6), 5077–5093.
156 M. Apergi, L. Eicke, A. Goldthau, J. Kurniawan, E. Schuch and S. Weko, Pathways to a sustainable electricity sector in Kenya: Challenges and transformational factors, *Util. Policy*, 2024, **91**, 101854.
157 S. K. Soonee, K. V. S. Baba, S. R. Narasimhan, S. C. Saxena, M. Joshi and K. P. Kumar, Grid integration of renewables in India, *Renew. Energy Integrat.*, 2017, 217–229.

158 L. Yan, C. Yongning, T. Haiyan, T. Xinshou, Z. Zhankui and J. Jianqing, Common focus and new requirement on technical standards of renewable energy grid integration, *Chin. Autom. Congr.*, 2019, 3719–3723.
159 P. Matschoss, B. Bayer, H. Thomas and A. Marian, The German incentive regulation and its practical impact on the grid integration of renewable energy systems, *Renewable Energy*, 2019, **134**, 727–738.
160 C. Li, Y. Zheng, Z. Li, L. Zhang, L. Zhang, Y. Shan and Q. Tang, Techno-economic and environmental evaluation of grid-connected and off-grid hybrid intermittent power generation systems, *Energy*, 2021, **230**, 120728.
161 P. Roy, M. Watkins, C. K. Iwuamadi and J. Ibrahim, Breaking the cycle of corruption in Nigeria's electricity sector: off-grid solutions for local enterprises, *Energy Res. Soc. Sci.*, 2023, **101**, 103130.
162 N. Wagner, M. Rieger, A. S. Bedi, J. Vermeulen and B. A. Demena, The impact of off-grid solar home systems in Kenya on energy consumption and expenditures, *Energy Econ.*, 2021, **99**, 105314.
163 J. N. Balls, Low-cost, adaptable solutions sell: Re-thinking off-grid solar diffusion at the bottom of the pyramid in India, *Energy Res. Soc. Sci.*, 2020, **70**, 101811.
164 PIB, India's Renewable Energy Capacity Hits New Milestone, 2024, available from: https://pib.gov.in/PressReleaseIframePage.aspx?PRID=2073038.
165 B. Bayer, P. Matschoss, H. Thomas and A. Marian, The German experience with integrating photovoltaic systems into the low-voltage grids, *Renewable Energy*, 2018, **119**, 129–141.
166 S. Dey, A. Sreenivasulu, G. T. N. Veerendra, K. V. Rao and P. A. Babu, Renewable energy present status and future potentials in India: An overview, *Innov. Green Dev.*, 2022, **1**(1), 100006.
167 L. C. Sim and S. Griffiths, Renewable energy supply chains between China and the Gulf states: Resilient or vulnerable?, *Energy Strategy Rev.*, 2024, **56**, 101605.
168 D. Manske, R. Lehneis and D. Thrän, The landscape of the renewable electricity supply–Municipal contributions to Germany's energy transition, *Renewable Energy*, 2025, **240**, 122172.
169 J. Pavlovic, L. Kostic, P. Bosnic, E. A. Kirkby and M. Nikolic, Interactions of silicon with essential and beneficial elements in plants, *Front. Plant Sci.*, 2021, **12**, 697592.
170 M. Yetano Roche, H. Verolme, C. Agbaegbu, T. Binnington, M. Fischedick and E. O. Oladipo, Achieving Sustainable Development Goals in Nigeria's power sector: assessment of transition pathways, *Clim. Policy*, 2020, **20**, 846–865.
171 O. A. Somoye, Energy crisis and renewable energy potentials in Nigeria: a review, *Renewable Sustainable Energy Rev.*, 2023, **188**, 113794.
172 J. Leigland and A. Eberhard, Localisation barriers to trade: the case of South Africa's renewable energy independent power program, *Dev. South. Afr.*, 2018, **35**, 569–588.
173 J. Hanto, A. Schroth, L. Krawielicki, P. Y. Oei and J. Burton, South Africa's energy transition–unraveling its political economy, *Energy Sustainable Dev.*, 2022, **69**, 164–178.
174 A. George, S. Boxiong, M. Arowo, P. Ndolo and J. Shimmon, Review of solar energy development in Kenya: opportunities and challenges, *Renew. Energ*, 2019, **29**, 123–140.
175 J. K. Kiplagat, R. Z. Wang and T. X. Li, Renewable energy in Kenya: resource potential and status of exploitation, *Renewable Sustainable Energy Rev.*, 2011, **15**, 2960–2973.
176 B. Klagge and C. Nweke-Eze, Financing large-scale renewable-energy projects in Kenya: investor types, international connections, and financialization, *Geogr. Ann. Ser. B*, 2020, **102**, 61–83.
177 E. Zigah and A. Creti, A comparative analysis of electricity access initiatives in Sub-Saharan Africa, in *Reg. Approaches Energy Transit. Multidiscip. Perspect.*, Springer Int. Publ., Cham, 2023, pp. 271–306.
178 G. A. Dino, A. Cavallo, A. Faraudello, R. Piercarlo and S. Mancini, Raw materials supply: Kaolin and quartz from ore deposits and recycling activities, *Resour. Policy*, 2021, **74**, 102413.
179 Z. Shan, J. Wu, P. He, Y. Zhao, K. Wei and W. Ma, Application Progress of Secondary Refining in Metallurgical Grade Silicon Purification Process, *Sep. Purif. Rev.*, 2025, 1–16.
180 F. Tian, Z. Pang, S. Hu, X. Zhang, F. Wang, W. Nie, *et al.*, Recent advances in electrochemical-based silicon production technologies with reduced carbon emission, *Research*, 2023, **6**, 0142.
181 A. G. Adeniyi, K. O. Iwuozor and E. C. Emenike, Material development potential of Nigeria's Kaolin, *Chem. Afr.*, 2023, **6**(4), 1709–1725.
182 G. A. Shiru, S. A. Mustapha and J. O. Mahmud, Availability of Raw Materials for Indigenous Manufacturing of Solar Photovoltaic Modules in Nigeria, *Nile J. Eng. Appl. Sci.*, 2023, **1**(1), 1–6.
183 J. Ramanujam, D. M. Bishop, T. K. Todorov, O. Gunawan, J. Rath, R. Nekovei, *et al.*, Flexible CIGS, CdTe and a-Si:H based thin film solar cells: A review, *Prog. Mater. Sci.*, 2020, **110**, 100619.
184 A. Maalouf, T. Okoroafor, Z. Jehl, V. Babu and S. Resalati, A comprehensive review on life cycle assessment of commercial and emerging thin-film solar cell systems, *Renewable Sustainable Energy Rev.*, 2023, **186**, 113652.
185 H. J. El-Khozondar, R. J. El-Khozondar, A. N. Sahmoud and Y. F. Nassar, Performance investigation of multilayer-layers solar cell based in ZnS-CZTSSe, *Sol. Energy*, 2025, **291**, 113410.
186 R. J. El-Khozondar, H. J. El-Khozondar and Y. F. Nassar, Efficiency performance of Ag-CdSe quantum dots nanocomposite sensitized solar cells, *Results Opt.*, 2023, **13**, 100516.
187 R. J. El-Khozondar, H. J. El-Khozondar, Y. F. Nassar, E. H. Bayoumi and H. Awad, Efficiency improvement of Ag-doped CdSe quantum dot sensitized solar cells, *Int. Eng. Conf. Renew. Energy Sustain. (ieCRES)*, 2023, pp. 1–5.
188 H. J. El-Khozondar, Y. F. Nassar, R. J. El-Khozondar and T. Djerafi, Simulation results for the PV cell based on the photonic crystal, *Optik*, 2022, **270**, 169966.

189 N. M. Zainudeen, L. Mohammed, A. Nyamful, D. Adotey and S. K. Osae, A comparative review of the mineralogical and chemical composition of African major bauxite deposits, *Heliyon*, 2023, **9**(8), e19070.
190 F. Abdulfattah, I. A. Rafukka and S. M. Manladan, Trends in characterization and beneficiation of non-ferrous metallic ores in Nigeria, *Charact. Miner., Met., Mater.*, 2020, 47–55.
191 P. Bowden, Gallium in younger granites of northern Nigeria, *Geochim. Cosmochim. Acta*, 1964, **28**(12), 1981–1988.
192 I. Kelechi, U. C. Eberechi and O. A. Ihuoma, The Use of Wide Band Gap Semiconductors in the Production of Electronic Devices and its Feasibility Study in Nigeria–Review, *Int. J. Adv. Sci. Eng.*, 2023, **10**, 3410–3421.
193 F. Di Giacomo, A. Fakharuddin, R. Jose and T. M. Brown, Progress, challenges and perspectives in flexible perovskite solar cells, *Energy Environ. Sci.*, 2016, **9**(10), 3007–3035.
194 D. Yang, R. Yang, S. Priya and S. Liu, Recent advances in flexible perovskite solar cells: fabrication and applications, *Angew. Chem., Int. Ed.*, 2019, **58**, 4466–4483.
195 Q. Dong, M. Chen, Y. Liu, F. T. Eickemeyer, W. Zhao, Z. Dai and Y. Shi, Flexible perovskite solar cells with simultaneously improved efficiency, operational stability, and mechanical reliability, *Joule*, 2021, **5**, 1587–1601.
196 B. Ozobialu, C. Emeh, O. Igwe, C. E. Nwoko, O. V. Omonona and E. A. Okoye, Environment-human bioaccumulation of lead resulting from artisanal lead-zinc mining activities in Ebonyi State, Southeastern Nigeria, *Soil Sediment Contam.*, 2023, **32**, 1095–1115.
197 J. C. Egbueri, J. C. Agbasi, J. O. Ighalo, H. C. Uwajingba and S. I. Abba, Lead, Nickel, Arsenic, and Chromium Contamination in Nigerian Groundwater: Sources, Potential Impacts, and Removal Techniques, in *Groundwater in Developing Countries: Case Studies from MENA, Asia and West Africa*, Springer, Cham, 2025, pp. 327–355.
198 F. C. Okoroigwe, E. C. Okoroigwe, O. O. Ajayi, S. N. Agbo and J. N. Chukwuma, Photovoltaic modules waste management: ethical issues for developing nations, *Energy Technol.*, 2020, **8**, 2000543.
199 Y. O. Kareem, E. K. Ameyaw, R. M. Amoah, O. A. Adegboye and S. Yaya, An assessment of Individual, community and state-level factors associated with inadequate iodised salt consumption among pregnant and lactating women in Nigeria, *BMC Pregnancy Childbirth*, 2023, **23**, 524.
200 C. U. Udeze, A. O. Nwokoye, J. C. Ejeka, I. L. Ikhioya and O. O. Anyanor, Investigating the influence of natural dye extracts from Ocimum gratissimum, Solanum melongena, Piper guineese, and their blend in the fabrication of perovskite solar cells, *Hybrid Adv.*, 2024, **6**, 100198.
201 A. A. Bayode, O. T. Ore, E. A. Nnamani, B. Sotunde, D. T. Koko, E. I. Unuabonah and M. O. Omorogie, Perovskite Oxides: Syntheses and Perspectives on Their Application for Nitrate Reduction, *ACS Omega*, 2024, **9**, 19770–19785.
202 S. Jiang, K. Wang, H. Zhang, Y. Ding and Q. Yu, Encapsulation of PV modules using ethylene vinyl acetate copolymer as the encapsulant, *Macromol. React. Eng.*, 2015, **9**, 522–529.
203 M. C. C. de Oliveira, A. S. A. D. Cardoso, M. M. Viana and V. D. F. C. Lins, The causes and effects of degradation of encapsulant ethylene vinyl acetate copolymer (EVA) in crystalline silicon photovoltaic modules: A review, *Renewable Sustainable Energy Rev.*, 2018, **81**, 2299–2317.
204 M. E. Obonukut, S. B. Alabi and P. G. Bassey, Steam reforming of natural gas: a value addition to natural gas utilization in Nigeria, *J. Chem. Chem. Eng.*, 2016, **1**, 28–41.
205 K. J. Geretschläger, G. M. Wallner and J. Fischer, Structure and basic properties of photovoltaic module backsheet films, *Sol. Energy Mater. Sol. Cells*, 2016, **144**, 451–456.
206 W. Gambogi, Y. Heta, K. Hashimoto, J. Kopchick, T. Felder, S. MacMaster and T. Sample, A comparison of key PV backsheet and module performance from fielded module exposures and accelerated tests, *IEEE J. Photovolt.*, 2014, **4**, 935–941.
207 M. Humood, A. Beheshti and A. A. Polycarpou, Surface reliability of annealed and tempered solar protective glasses: Indentation and scratch behavior, *Sol. Energy*, 2017, **142**, 13–25.
208 Trading Economies, Nigeria Imports of Glass and glassware, 2024, available from: **https://tradingeconomics.com/nigeria/imports/glass-glassware**.
209 Federal Institute of Industrial Research, Oshodi (FIIRO), Project development and design department, 2023, available from: **https://www.fiiro.gov.ng/index.php/departments/project-development-and-design**.
210 M. Musiał, L. Lichołai and D. Katunský, Modern thermal energy storage systems dedicated to autonomous buildings, *Energies*, 2023, **16**, 4442.
211 C. Tong and C. Tong, Advanced Materials Enable Renewable Wind Energy Capture and Generation, in *Introduction to Materials for Advanced Energy Systems*, 2019, pp. 379–444.
212 D. M. P. Mingos, The discovery of the elements in the periodic table, in *The Periodic Table I: Historical Development and Essential Features*, 2019, pp. 1–57.
213 P. Nunez and S. Jones, Cradle to gate: life cycle impact of primary aluminium production, *Int. J. Life Cycle Assess.*, 2016, **21**, 1594–1604.
214 X. Wang, H. Lu, H. Ni, W. Lu, M. Zhang and Y. Zhang, Research Progress of Border for Solar Photovoltaic Modules, in *Int. Conf. Chem. Mater. Food Eng.*, Atlantis Press, 2015, pp. 289–293.
215 A. Thakur and A. Kumar, Technologies Based on Reusable Wind Turbine Blades, in *Wind Energy Storage and Conversion: from Basics to Utilities*, 2024, pp. 133–183.
216 A. A. Mas'ud, A. V. Wirba, J. A. Ardila-Rey, R. Albarracín, F. Muhammad-Sukki, Á. Jaramillo Duque and A. B. Munir, Wind power potentials in Cameroon and Nigeria: lessons from South Africa, *Energies*, 2017, **10**, 443.
217 T. R. Ayodele, A. S. O. Ogunjuyigbe and T. O. Amusan, Wind power utilization assessment and economic analysis of

wind turbines across fifteen locations in the six geographical zones of Nigeria, *J. Cleaner Prod.*, 2016, **129**, 341–349.
218 G. K. Akporhonor, S. O. Otuagoma and T. A. Akporhonor, Nigerian wind energy status, *J. Wind Eng.*, 2024, **48**, 310–322.
219 I. A. Okewale, O. E. Olamijulo and B. M. Olaleye, Investigation into the mechanical behaviour of silica rich bituminous sand, *Geotech. Geol. Eng.*, 2023, **41**, 3359–3374.
220 E. M. Ezeh, Advances in the development of polyester resin composites: a review, *World J. Eng.*, 2024, DOI: 10.1108/WJE-12-2023-0517.
221 M. Rani, P. Choudhary, V. Krishnan and S. Zafar, A review on recycling and reuse methods for carbon fiber/glass fiber composites waste from wind turbine blades, *Composites, Part B*, 2021, **215**, 108768.
222 D. K. Rajak, P. H. Wagh and E. Linul, Manufacturing technologies of carbon/glass fiber-reinforced polymer composites and their properties: A review, *Polymers*, 2021, **13**, 3721.
223 Y. S. Mohammed, M. W. Mustafa, N. Bashir and I. S. Ibrahem, Existing and recommended renewable and sustainable energy development in Nigeria based on autonomous energy and microgrid technologies, *Renewable Sustainable Energy Rev.*, 2017, **75**, 820–838.
224 K. O'Leary, V. Pakrashi and D. Kelliher, Optimization of composite material tower for offshore wind turbine structures, *Renewable Energy*, 2019, **140**, 928–942.
225 M. X. Tao, Y. L. Wang, Z. Y. Ma and J. Z. Zhao, Experimental database and analysis of in-plane seismic behaviour of double steel-plate composite walls for wind power tower, *Thin-Walled Struct.*, 2024, **200**, 111917.
226 O. Adegbite, The Nigerian Steel Industry: Retrospect and Prospect, in: *Perspectives on Industrial Development in Nigeria: Issues, Challenges and Hard Choices*, 2021, pp. 79–103.
227 S. I. Azubuike, S. Nakanwagi and J. Pinto, Mining Resource Corridor development in Nigeria: critical considerations and actions for a diversified and sustainable economic future, *Miner. Econ.*, 2023, **36**, 59–75.
228 F. I. Abam, B. N. Nwankwojike, O. S. Ohunakin and S. A. Ojomu, Energy resource structure and on-going sustainable development policy in Nigeria: a review, *Int. J. Energy Environ. Eng.*, 2014, **5**, 1–16.
229 P. D. Jensen, P. Purnell and A. P. Velenturf, Highlighting the need to embed circular economy in low carbon infrastructure decommissioning: The case of offshore wind, *Sustain. Prod. Consum.*, 2020, **24**, 266–280.
230 A. Mathern, C. von der Haar and S. Marx, Concrete support structures for offshore wind turbines: Current status, challenges, and future trends, *Energies*, 2021, **14**, 1995.
231 C. Li, J. M. Mogollón, A. Tukker, J. Dong, D. von Terzi, C. Zhang and B. Steubing, Future material requirements for global sustainable offshore wind energy development, *Renewable Sustainable Energy Rev.*, 2022, **164**, 112603.
232 J. Li, Z. Wu, C. Shi, Q. Yuan and Z. Zhang, Durability of ultra-high performance concrete–A review, *Constr. Build. Mater.*, 2020, **255**, 119296.
233 M. A. Etim, K. Babaremu, J. Lazarus and D. Omole, Health risk and environmental assessment of cement production in Nigeria, *Atmosphere*, 2021, **12**, 1111.
234 A. A. Shah and Y. Ribakov, Recent trends in steel fibered high-strength concrete, *Mater. Des.*, 2011, **32**, 4122–4151.
235 H. Hao, K. Bi, W. Chen, T. M. Pham and J. Li, Towards next generation design of sustainable, durable, multi-hazard resistant, resilient, and smart civil engineering structures, *Eng. Struct.*, 2023, **277**, 115477.
236 V. Afroughsabet, L. Biolzi and T. Ozbakkaloglu, High-performance fiber-reinforced concrete: a review, *J. Mater. Sci.*, 2016, **51**, 6517–6551.
237 R. Ruiz, L. Todisco and H. Corres, Application of high-performance fibre reinforced concrete to precast girders for road bridges: Conceptual considerations and numerical analyses, *Struct. Concr.*, 2023, **24**, 4645–4659.
238 M. H. Akeed, S. Qaidi, R. H. Faraj, S. S. Majeed, A. S. Mohammed, W. Emad and A. R. Azevedo, Ultra-high-performance fiber-reinforced concrete. Part V: Mixture design, preparation, mixing, casting, and curing, *Case Stud. Constr. Mater.*, 2022, **17**, e01363.
239 A. Giwa, A. Alabi, A. Yusuf and T. Olukan, A comprehensive review on biomass and solar energy for sustainable energy generation in Nigeria, *Renewable Sustainable Energy Rev.*, 2017, **69**, 620–641.
240 M. Diacono, A. Persiani, E. Testani, F. Montemurro and C. Ciaccia, Recycling agricultural wastes and by-products in organic farming: Biofertilizer production, yield performance and carbon footprint analysis, *Sustainability*, 2019, **11**, 3824.
241 M. R. Cherubin, D. M. D. S. Oliveira, B. J. Feigl, L. G. Pimentel, I. P. Lisboa, M. R. Gmach and C. C. Cerri, Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth: A review, *Sci. Agric.*, 2018, **75**, 255–272.
242 R. Gómez-García, D. A. Campos, C. N. Aguilar, A. R. Madureira and M. Pintado, Valorisation of food agro-industrial by-products: From the past to the present and perspectives, *J. Environ. Manage.*, 2021, **299**, 113571.
243 Statista, Nigeria: paddy rice production quantity 2023, 2025n, available from: https://www.statista.com/statistics/1300736/production-volume-of-paddy-rice-in-nigeria/.
244 International Production Assessment Division (IPAD), Nigeria rice area, yield and production, 2024, available from: https://ipad.fas.usda.gov/countrysummary/Default.aspx?id=NI&crop=Rice.
245 X. Tian, H. Zhang and C. Sheng, Self-heating of agricultural residues during storage and its impact on fuel properties, *Energy Fuels*, 2017, **32**, 4227–4236.
246 Y. Singh, S. Sharma, U. Kumar, P. Sihag, P. Balyan, K. P. Singh and O. P. Dhankher, Strategies for economic utilization of rice straw residues into value-added by-products and prevention of environmental pollution, *Sci. Total Environ.*, 2024, **906**, 167714.

247 C. G. L. Grotto, C. J. G. Colares, D. R. Lima, D. H. Pereira and A. T. do Vale, Energy potential of biomass from two types of genetically improved rice husks in Brazil: A theoretical-experimental study, *Biomass Bioenergy*, 2020, **142**, 105816.
248 E. A. Adebowale, Maize residues as ruminant feed resources in Nigeria, *Cell*, 1988, **9**, 4–7.
249 Statista, Volume of cassava produced in Africa as of 2022, by country, 2025i, available from: https://www.statista.com/statistics/1497947/cassava-production-volume-in-africa-by-country/.
250 I. Okike, S. Wigboldus, A. Samireddipalle, D. Naziri, A. O. Adesehinwa, V. A. Adejoh and P. Kulakow, Turning waste to wealth: Harnessing the potential of cassava peels for nutritious animal feed, in *Root, Tuber and Banana Food System Innovations: Value Creation for Inclusive Outcomes*, Springer, Cham, 2022, pp. 173–206.
251 Statista, Total volume of yam production in Africa 2022, by country, 2025j, available from: https://www.statista.com/statistics/1499222/africa-volume-of-yam-production-by-country/.
252 E. O. Ajala, M. A. Ajala, O. O. Onoriemu, S. G. Akinpelu and S. H. Bamidele, Lactic acid production: Utilization of yam peel hydrolysate as a substrate using Rhizopus orysae in kinetic studies, *Biofuels, Bioprod. Biorefin.*, 2021, **15**, 1031–1045.
253 Statista, Sorghum production by leading country worldwide 2024/25, 2025k, available from: https://www.statista.com/statistics/1134651/global-sorghum-production-by-country/#:~:text=In2024%2F25%2CtheUnited,millionmetrictonsofsorghum.
254 M. Nasidi, R. Agu, Y. Deeni and G. Walker, Utilization of whole sorghum crop residues for bioethanol production, *J. Inst. Brew.*, 2016, **122**, 268–277.
255 Statista, Nigeria: growth in production of millet 2023, 2025l, available from: https://www.statista.com/statistics/1134509/percentage-change-in-production-of-millet-in-nigeria/.
256 A. Kuhe, A. V. Terhemba and H. Iortyer, Biomass valorization for energy applications: A preliminary study on millet husk, *Heliyon*, 2021, **7**, e07818.
257 L. M. Mohlala, M. O. Bodunrin, A. A. Awosusi, M. O. Daramola, N. P. Cele and P. A. Olubambi, Beneficiation of corncob and sugarcane bagasse for energy generation and materials development in Nigeria and South Africa: A short overview, *Alexandria Eng. J.*, 2016, **55**, 3025–3036.
258 G. B. Taphee, A. A. U. Jongur, D. Y. Giroh and E. I. Jen, Analysis of profitability of groundnut production in northern part of Taraba State, Nigeria, *Int. J. Comput. Appl.*, 2015, 125.
259 U. Prajapati, R. Kaushik and S. Kumar, Groundnut Meal: Scientific Interventions for Achieving Superior Quality of Protein, in *Oilseed Meal as a Sustainable Contributor to Plant-Based Protein: Paving the Way towards Circular Economy and Nutritional Security*, Springer, Cham, 2024, pp. 53–79.
260 D. O. Obada, M. O. Kekung, T. Levonyan and G. W. Norval, Palm oil mill derived empty palm fruit bunches as a feed stock for renewable energy applications in Nigeria: A review, *Bioresour. Technol. Rep.*, 2023, 101666.
261 Statista, Cocoa bean production Nigeria 2023/2024, 2025m, available from: https://www.statista.com/statistics/497865/production-of-cocoa-beans-in-nigeria/#:~:text=ProductionofcocoabeansinNigeria2012%2F2013%2D22023%2F2024&text=Accordingtothereport%2CNigeria,thousandtonsin2023%2F2024.
262 T. O. Ajewole, F. B. Elehinafe, O. B. Okedere and T. E. Somefun, Agro-residues for clean electricity: A thermo-property characterization of cocoa and kolanut waste blends, *Heliyon*, 2021, **7**, e08060.
263 R. Ahorsu, F. Medina and M. Constantí, Significance and challenges of biomass as a suitable feedstock for bioenergy and biochemical production: A review, *Energies*, 2018, **11**, 3366.
264 FAOSTAT, Cowpeas, Dry, 2021, available from: https://www.fao.org/faostat/en/#data/QCL.
265 C. M. Ebisi, Biomass Resources and Energy Access in Nigeria: A Scoping Review, *Nat. Gas*, 2024, **378**, 25.
266 Z. M. Bundhoo, Potential of bio-hydrogen production from dark fermentation of crop residues: a review, *Int. J. Hydrogen Energy*, 2019, **44**, 17346–17362.
267 M. A. Qyyum, S. F. A. Shah, K. Qadeer, A. Naquash, M. Yasin, M. Rehan and A. S. Nizami, Biowaste to bioenergy options for sustainable economic growth opportunities in developing countries: Product space model analysis and policy map development, *Renewable Sustainable Energy Rev.*, 2022, **169**, 112832.
268 J. Vasco-Correa, S. Khanal, A. Manandhar and A. Shah, Anaerobic digestion for bioenergy production: Global status, environmental and techno-economic implications, and government policies, *Bioresour. Technol.*, 2018, **247**, 1015–1026.
269 G. Rajashekar, R. Fararoda, R. S. Reddy, C. S. Jha, K. N. Ganeshaiah, J. S. Singh and V. K. Dadhwal, Spatial distribution of forest biomass carbon (Above and below ground) in Indian forests, *Ecol. Indic.*, 2018, **85**, 742–752.
270 O. B. Okedere, B. S. Fakinle, J. A. Sonibare, F. B. Elehinafe and O. A. Adesina, Particulate matter pollution from open burning of sawdust in Southwestern Nigeria, *Cogent Environ. Sci.*, 2017, **3**, 1367112.
271 M. O. Martin-Guay, A. Paquette, P. B. Reich and C. Messier, Implications of contrasted above-and below-ground biomass responses in a diversity experiment with trees, *J. Ecol.*, 2020, **108**, 405–414.
272 K. G. MacDicken, Global forest resources assessment 2015: what, why and how?, *For. Ecol. Manage.*, 2015, **352**, 3–8.
273 T. Väisänen, A. Haapala, R. Lappalainen and L. Tomppo, Utilization of agricultural and forest industry waste and residues in natural fiber-polymer composites: A review, *Waste Manage.*, 2016, **54**, 62–73.
274 A. Kumar, S. Adamopoulos, D. Jones and S. O. Amiandamhen, Forest biomass availability and

utilization potential in Sweden: A review, *Waste Biomass Valorization*, 2021, **12**, 65–80.

275 I. Majumdar, K. A. Campbell, J. Maure, I. Saleem, J. Halasz and J. Mutton, Forest bioeconomy in Ontario–A policy discussion, *For. Chron.*, 2017, **93**, 21–31.

276 E. Hurmekoski, R. Jonsson, J. Korhonen, J. Jänis, M. Mäkinen, P. Leskinen and L. Hetemäki, Diversification of the forest industries: role of new wood-based products, *Can. J. For. Res.*, 2018, **48**, 1417–1432.

277 B. Ali, N. Saadun, N. Kamarudin, M. A. Alias, N. M. Nawi and B. Azhar, Fuelwood value chain in Northern Nigeria: economic, environment, and social sustainability concerns, *Forests*, 2023, **14**, 906.

278 T. O. Babatunde, O. O. Babatunde and K. O. Babatunde, Economic Analysis of Sawn Wood Production and Determinants of Sawn Wood Supply in Selected Sawmill in Ijebu-Ode Local Government Area of Ogun State Nigeria, *J. Bioresour. Manage.*, 2022, **9**, 4.

279 FAO, Present status of the forestry sector of Nigeria, 2001, available from: https://www.fao.org/4/ab592e/ab592e03.htm.

280 R. Bailis, Y. Wang, R. Drigo, A. Ghilardi and O. Masera, Getting the numbers right: revisiting woodfuel sustainability in the developing world, *Environ. Res. Lett.*, 2017, **12**, 115002.

281 Y. S. Mohammed, N. Bashir and M. W. Mustafa, Overuse of wood-based bioenergy in selected sub-Saharan Africa countries: review of unconstructive challenges and suggestions, *J. Cleaner Prod.*, 2015, **96**, 501–519.

282 B. D. Titus, K. Brown, H. S. Helmisaari, E. Vanguelova, I. Stupak, A. Evans and P. Reece, Sustainable forest biomass: A review of current residue harvesting guidelines, *Energy Sustain. Soc.*, 2021, **11**, 1–32.

283 A. Miskam, Z. A. Zainal and I. M. Yusof, Characterization of Sawdust Residues for Cyclone Gasifier, *J. Appl. Sci.*, 2009, **9**, 2294–2300.

284 Forest Research, Typical calorific values of fuels, 2025, available from: https://www.forestresearch.gov.uk/tools-and-resources/fthr/biomass-energy-resources/reference-biomass/facts-figures/typical-calorific-values-of-fuels/.

285 Ł. Sobol, D. Sabat and A. Dyjakon, Assessment of Bark Properties from Various Tree Species in Terms of Its Hydrophobicity and Energy Suitability, *Energies*, 2023, **16**, 6586.

286 O. J. Odejobi, O. O. Ajala and F. N. Osuolale, Review on potential of using agricultural, municipal solid and industrial wastes as substrates for biogas production in Nigeria, *Biomass Convers. Biorefin.*, 2024, **14**, 1567–1579.

287 E. E. Okoro, I. S. Okafor, K. C. Igwilo, K. B. Orodu and A. O. Mamudu, Sustainable biogas production from waste in potential states in Nigeria–alternative source of energy, *J. Contemp. Afr. Stud.*, 2020, **38**, 627–643.

288 J. F. Akinbami, M. O. Ilori, T. O. Oyebisi, I. O. Akinwumi and O. Adeoti, Biogas energy use in Nigeria: current status, future prospects and policy implications, *Renewable Sustainable Energy Rev.*, 2001, **5**(1), 97–112.

289 O. C. Okeh, C. O. Onwosi and F. J. C. Odibo, Biogas production from rice husks generated from various rice mills in Ebonyi State, Nigeria, *Renewable Energy*, 2014, **62**, 204–208.

290 O. Adeoti, T. A. Ayelegun and S. O. Osho, Nigeria biogas potential from livestock manure and its estimated climate value, *Renewable Sustainable Energy Rev.*, 2014, **37**, 243–248.

291 S. Qian, L. Chen, S. Xu, C. Zeng, X. Lian, Z. Xia and J. Zou, Research on Methane-Rich Biogas Production Technology by Anaerobic Digestion Under Carbon Neutrality: A Review, *Sustainability*, 2025, **17**, 1425.

292 A. O. Akintunde, I. Mustofa, L. C. Ndubuisi-Ogbonna, O. O. Oyekale and B. A. Shobo, Exploring the Genetic Diversity: A Review of Germplasm in Nigerian Indigenous Goat Breeds, *Small Rumin. Res.*, 2024, 107236.

293 F. O. Fasina, M. Agbaje, F. L. Ajani, O. A. Talabi, D. D. Lazarus, C. Gallardo and A. D. Bastos, Risk factors for farm-level African swine fever infection in major pig-producing areas in Nigeria, 1997–2011, *Prev. Vet. Med.*, 2012, **107**, 65–75.

294 M. R. Atelge, D. Krisa, G. Kumar, C. Eskicioglu, D. D. Nguyen, S. W. Chang and S. Unalan, Biogas production from organic waste: recent progress and perspectives, *Waste Biomass Valorization*, 2020, **11**, 1019–1040.

