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SUSTAINABLE ENERGY DEVELOPMENT IN NIGERIA: PRESENT AND THE FUTURE- A REVIEW

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ABSTRACT: Nigeria has large reserves of renewable energy yet it still experiences chronic energy poverty, poor infrastructure and over reliance on fossil fuels. Although the country is determined to reach net-zero emissions by 2060, the unit consumption of electricity is among the lowest in the world, and most of the citizens continue to have no dependable access to electricity. This review critically analyses the prevailing energy situation, the technical potential of renewable resources, and the systemic issues of fragile institutional frameworks, patchy policies, inadequate financing and gaps in technological capacity that limit the pace of improvement. It also analyses national policy tools like the Renewable Energy Master Plan, Vision 2030 and the Energy Transition Plan and government, the private sector, donors and community-based initiatives. Other technological advances described in the paper as key facilitators of sustainable energy access include off-grid mini-grids, smart grids, and advanced storage systems. It concludes that to deliver the energy and climate targets in Nigeria, a coordinated governance architecture, mixed financing system, investment in human capacity, and extensive stakeholder participation is needed.

Keywords: Biomass, Energy access, Geothermal energy, Nigeria, Renewable energy, Solar energy, Sustainable energy

1. INTRODUCTION

The development of sustainable energy has taken centre stage globally, as a result of the twin reasons to cut carbon emission and to increase the availability of affordable and reliable energy services. Nigeria is an example of a dramatic paradox: the largest economy and the most populous country in Africa, with an estimated 37.5 billion barrels of oil, 209 trillion cubic feet of gas, and enormous potential of renewable energy, there the situation of energy poverty is a permanent one (IEA, 2024; Games, 2021). Electricity use is approximately at 150 kWh per year, one of the poorest in the world, and more often than not, blackouts and the use of polluting diesel generators ruin the growth prospects and the quality of life (Adeshina et al., 2024; Oyedepo, 2014). The availability of energy is a technical challenge related to economic development as well as a condition that precedes economic growth, social equality, and political steadiness (Oyedepo, 2012a; Elum & Momodu, 2017). The problem is severe in Nigeria: two out of three or four Nigerians do not have access to electricity, and electrification rates in rural areas are less than 25% (Sobajo, 2024; Ogunleye et al., 2022). Its effects are restricted industrial performance, inadequate service provision in education and health, and a high reliance on traditional biomass, which leads to deforestation and indoor air contamination (Shaaban and Petinrin, 2014; Oseni, 2012a).

The focus on developing sustainable energy, which is defined as the need to balance economic growth with environmental stewardship by implementing renewable energy and making effective use of conventional resources (Emodi & Boo, 2015), is considered the core of the development agenda in Nigeria. It is also consistent with other international obligations including the Sustainable Development Goals (SDG 7: Affordable and Clean

Energy), the New York agreement on the climate change (Wernersson et al., 2024). The development of solar, wind, hydro, and biomass energy solutions will provide Nigeria with the chance at enhancing energy security, industrializing the country, providing employment, and cutting emissions (Mohammed et al., 2017; Li & Li, 2023; Rajendran et al., 2024). The review presents a critical synthesis of the existing energy situation in Nigeria, the potential of renewable energies in Nigeria, institutional and financial issues and initiatives. It also presents emerging technology solutions and offers strategic guidance to accelerate the process to universal access and energy futures.

2. CURRENT ENERGY LANDSCAPE IN NIGERIA

2.1. Overview

Nigeria is the biggest economy in Africa in terms of GDP and population, but the access rate of electricity is among the lowest in the continent. Only approximately 61.2% of the population have access to electricity, with rural access lagging at below 25 percent and urban access at over 80 percent (World Bank, 2024; World Bank, 2025; Adegbesan, 2025). This divide is an indication of profound structural inadequacies in infrastructure and governance. In contrast, according to Figure 1, some of the countries like Egypt, Morocco, and South Africa have recorded almost universal access (Energy Capital & Power, 2022).

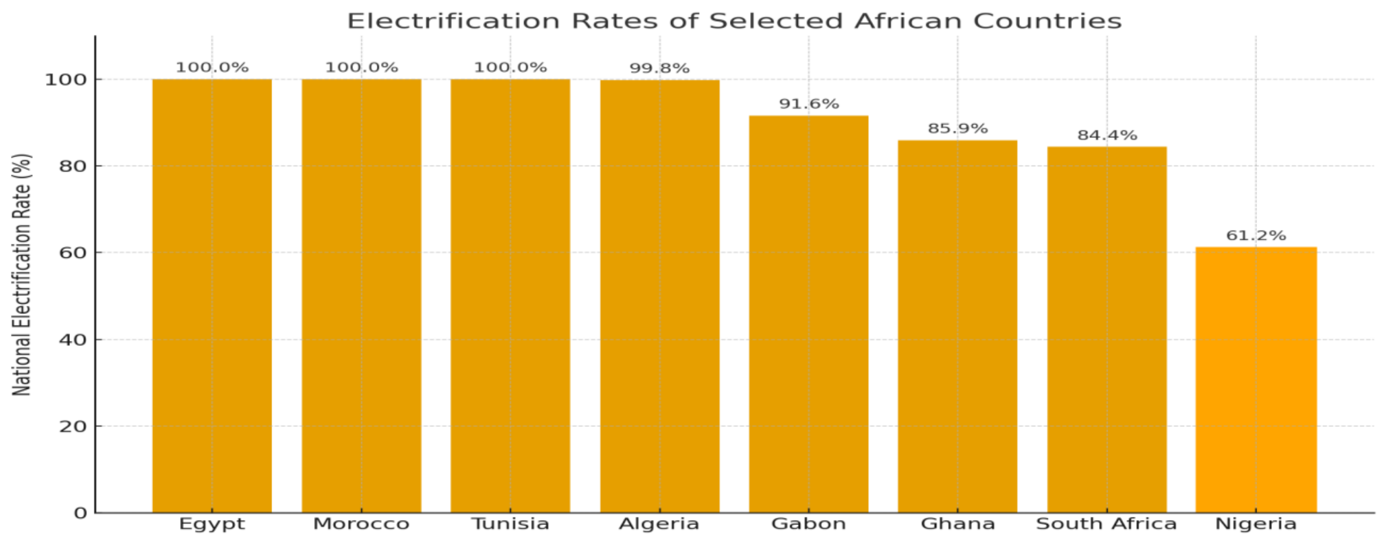

Figure 1. Access to Electricity (%) (Source: Energy Capital & Power, 2022).

Emodi and Yusuf (2015) state that Nigeria has a bad rating in electricity access, compared to the ten leading economies on the continent (Figure 1). These efforts have however been fruitless because the country has been facing a sustained electricity crisis irrespective of various government interventions. Energy Capital & Power (2022) confirms that Egypt, Morocco and Tunisia are already enjoying universal access to electricity with each country recording a 100 national electrification rate. In Algeria, the country is almost at the 100 per cent coverage. Gabon has 91.6, Ghana has 85.9 and South Africa has 84.4. Interestingly, even Nigeria, which is one of the largest electricity generators in Africa is way below all these levels and does not feature among states where the national electrification rates are the highest. Combined, these sources of data demonstrate the acutely high structural energy poverty in Nigeria, both on an absolute (per capita availability of electricity) and on a relative (i.e. when compared to other countries and continents) basis. The ensuing electricity shortfall serves as a limitation on industrialization of developing economies, deteriorates social investments in education and health and drives households and small businesses to inefficient and polluting alternatives like diesel generators. Fossil fuels dominate the sector, and oil, gas, and coal comprise more than 80 percent of primary energy sources (Eweka et al., 2022; Elehinafe et al., 2021). Smaller-scale hydro is the largest source of renewables, under 20 percent, with solar, wind, and biomass being underused (Esan et al., 2019). The economy is also vulnerable to global energy market volatility due to the fact that Nigerians are importing refined petroleum products and run self-generation on diesel (Oyedepo, 2014; Ohunakin, 2010). In addition, on electricity production, according to the data (Figure 2) published by the International Energy Agency (IEA, 2024), South Africa, Egypt and Algeria are the top electricity generators in Africa with production capacities of 25.9, 23.1 and 10.1 percent of the electricity in the continent respectively. Morocco comes second with a figure of 4.7, and Nigeria comes fifth with a figure of 37,915 GWh as the total electricity production in Africa is considered to be 4.2. Other significant contributors are Libya (3.9%), Ghana (2.6%), Tunisia (2.4%), Mozambique (2.2%) and Zambia (2.2%). Figure 2 shows clearly how the gap in output is much wider and that South Africa and Egypt alone contribute close to half of the electricity generated in Africa which is far ahead of the contributions of the other countries. This ranking highlights the fact that Nigeria is an important yet quite a small actor in the electricity sector in Africa, particularly when compared to South Africa and Egypt.

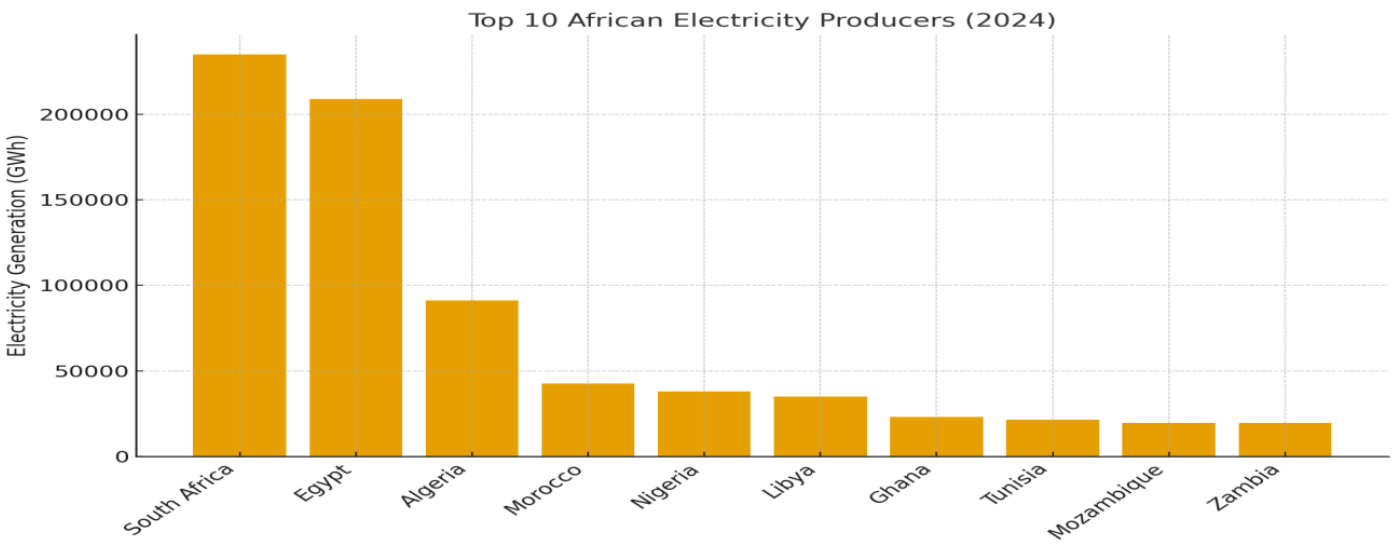

Figure 2. Electricity Production (MWh) (Source: IEA, 2024; Adekunle, 2024).

In another development, GlobalEconomy in (2025) has noted that the power generation capacity of Nigeria is 3.34 million kilowatts, and this ranks 13th in Africa. This also ranks Nigeria way below the top producers on the continent: South Africa (65.87 million kilowatts), Egypt (59.3 million kilowatts), and Algeria (22.59 million kilowatts). These data points, 1980-2023, represent the comparatively low level of generation capacity of Nigeria in comparison with the top economies in Africa. The per capita consumption of electricity is impressively low (only 144 kWh), as opposed to the global average of 3,260 kWh (Oseni, 2012a; Oseni, 2012b). Nigeria is a nation dependent largely on fossil fuel especially oil and gas which forms about 80% of the primary energy source in the country and renewable energy forms less than 15, which makes the country susceptible to energy dynamics in world markets and erratic domestic policy (Eweka et al., 2022; Ohunakin, 2010). Continuous problems such as long-term inadequate investment in infrastructure, governance, and inconsistencies in certain policies have limited energy availability and reliability (Oyedepo, 2014; Abe et al., 2024). Despite attempts by recent reforms like the Electric Power Sector Reform Act 2005 and the National Renewable Energy and Energy Efficiency Policy 2015 to liberalize and modernize the sector, their effects have not been impactful as the gaps in implementation (Lawal, 2021).

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2.2. Infrastructure Performance

The Nigerian power industry is characterized by the absurd gap between the declared generation and the real generation. The country has an installed grid-connected capacity of around 13,625 MW comprising 28 power stations as indicated in Table 1, but based on Figure 1 on the NERC Q1 2025 quarterly performance report, the average generation was 5,296.89 MW in Q4 2024 and 5,336.88 MW in Q1 2025, or 39% operational efficiency (NERC, 2025).

Table 1: Nigeria's power plant operational performance for 28 power stations

S/N	Power Station Name	Installed Capacity (MW) (A)	Average Available Capacity (MW) (B) 2024 /Q4	2025/Q1
1	Ikeja_1	110	108.96	109.1
2	Ihovbor_2	461	445.68	446.36
3	Jebba_1	578	451.2	447.15
4	Kainji_1	760	491.08	501.58
5	Okapi_1	480	262.45	282.72
6	Odukpani_1	625	387.87	346.87
7	Shiroro_1	600	371.01	332.86
8	Delta_1	900	341.17	489.8
9	Geregu_2	435	224.46	227.29
10	Omotosho_1	335	190.11	166.05
11	Zungeru_1	700	332.81	345.7
12	Olorunsogo_1	335	180.66	161.81
13	Egbin_1	1320	614.72	607.83
14	Igbafo_1	45	19.24	20.23
15	Dadin-Kowa_1	40	34.74	16.36
16	Afam_2	650	199.43	246.63
17	Geregu_1	435	119.59	138.03
18	Rivers_1	180	51.53	52.86
19	Omoku_1	150	44.27	38.85
20	Sapele_2	500	83.95	97.91
21	Ibom Power_1	190	32.44	23.46
22	Omotosho_2	500	12.04	60.85
23	Ihovbor_1	500	65.09	51.32
24	Afam_1	726	58.18	73.48
25	Sapele Stream_1	720	63.25	39.61
26	Olorunsogo_2	750	109.08	37.43
27	Trans Amadi_1	100	1.85	4.75
28	Alaoji_1	500	0	0

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Total =	**13,625**	**5,296.89**	**5,336.88**

The average transmission and distribution losses are 25-45%, approximately equal to an annual economic loss of 1.4 billion (Adedokun et al., 2023). An analysis of plant-level performance reveals that a number of large plants, such as Shiroro, Delta, and Sapele, run at substantially lower capacities because of bad maintenance and lack of gas and grid volatility (NERC, 2025). These values point out the vulnerability of the generation system in Nigeria. The population of more than 225 million would mean that one of the lowest available capacities is less than 25 W per capita (World Bank, 2023; World Bank, 2024). There are eleven electricity distribution companies (DISCOs) in Nigeria that are current on distribution. They are Kaduna, Kano, Yola, Jos, Abuja, Ibadan, Ikeja, Eko, Benin, Port Harcourt, and Enugu DISCOs as shown on Figure 3 (Taofeek, 2024; Adoghe et al., 2023). Figure 3 provides a descriptive representation of the geographical location of the eleven existing electricity distribution companies (DISCOs) in operation in Nigeria. The decentralized nature of power distribution in the country is characterized by each DISCO having its own distribution of electric power in certain areas or designated states. Figure 3 map illustrates the division of power distribution network of Nigeria in geopolitical zones. E.g.: Kaduna, Kano, Yola and Jos DISCOs are located mostly in the north of the country. Abuja DISCO is in charge of the capital and the outer regions in the central zone. The southwest has Ibadan, Ikeja and Eko DISCOS that cover the Lagos region and its closely measured areas. The south-south zone encompasses key oil-producing regions and it is controlled by Benin and Port Sokoro DISCOs. The south east serves under Enugu DISCO. This structure implies a purposeful effort to decentralize powers of authority according to population density, industrialization, and local needs. But even under such systematic structure, the map also indirectly emphasizes the persistent problems in the distribution of power, including inefficiencies, lack of access, and excessive technical and commercial losses in some areas. Through the visual grouping of the DISCOs, Figure 3 aids in policy debate concerning the issue of regional infrastructure investing, regulatory controls, and how reorganizing, or even establishing regional cooperation, may enhance service delivery.

Figure 3: Electricity distribution companies in Nigeria (Taofeek, 2024; Adoghe et al., 2023)

2.3. Regional Disparities and Access

In Nigeria, access to energy is characterised by clear imbalances across regions. In urban areas like Lagos and Abuja, over 85 percent are electrified, rural electrification rates are 24 years on average, and in the North-East, 14 percent because of insecurity and lack of investment (Oseni, 2012b). Most of the rural households rely on traditional biomass like firewood and charcoal, which contributes close to 75 percent of household energy consumption (Emodi and Boo, 2015). The social aspects of these inequalities are also quite clear and direct: women in rural areas are spending three to five hours every day to gather firewood, which leaves less time to study and gain income (Ohunakin, 2010; Emodi and Boo, 2015). These disparities underscore the means to respond with urgent decentralized renewable energy capabilities in solar mini-grids and stand-alone systems, which are currently being implemented in underserved regions (Oseni, 2012b).

2.4. Energy Consumption Patterns

In Nigeria, the growth of population, urbanization, and economic framework determine energy use. Residential sector comprises approximately 55 percent of the energy consumption, which primarily consists of cooking and lighting, then industry (25 percent) and transport (20 percent) (Oseni, 2012b; Ohunakin, 2010). There is scarcity of modern fuel with firewood prevailing in the home (60%), kerosene (20%), and LPG (5%) (Oseni, 2012b). Waste and inefficiencies abound. It is estimated that energy productivity losses contribute to 2–5% to GDP every year (Okoroafor et al., 2022; Olaoye et al., 2016). Unreliable electricity is a detriment to industrial competitiveness as firms have developed a heavy reliance on self-generation because of this factor, especially diesel and petrol generators. The 60-plus GW cumulative generator capacity surpasses that of the national grid, yet at excessive financial,

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health, and environmental costs (Edomah, 2016; Ulpiani et al., 2024). Gradual progress is evident. Solar home systems adoption is increasing an average of 25 percent every year with the help of the declining photovoltaic prices and other programs like the Nigeria Electrification Project (Abe et al., 2024). Yet, unless significant changes are made, the structural imbalance between demand and supply will remain present.

3. RENEWABLE ENERGY POTENTIALS IN NIGERIA

Nigeria is richly endowed with solar, wind, hydropower, biomass, and geothermal, which are renewable energy sources that can make significant contributions to sustainable energy development (Abe et al., 2024; Eweka et al., 2022; Yahaya et al., 2018). The renewable energy situation in Nigeria is plotted in Figure 4 to reflect on dominant resource access within the states, with states color-coded as wind, hydro, solar, or hybrid energy systems.

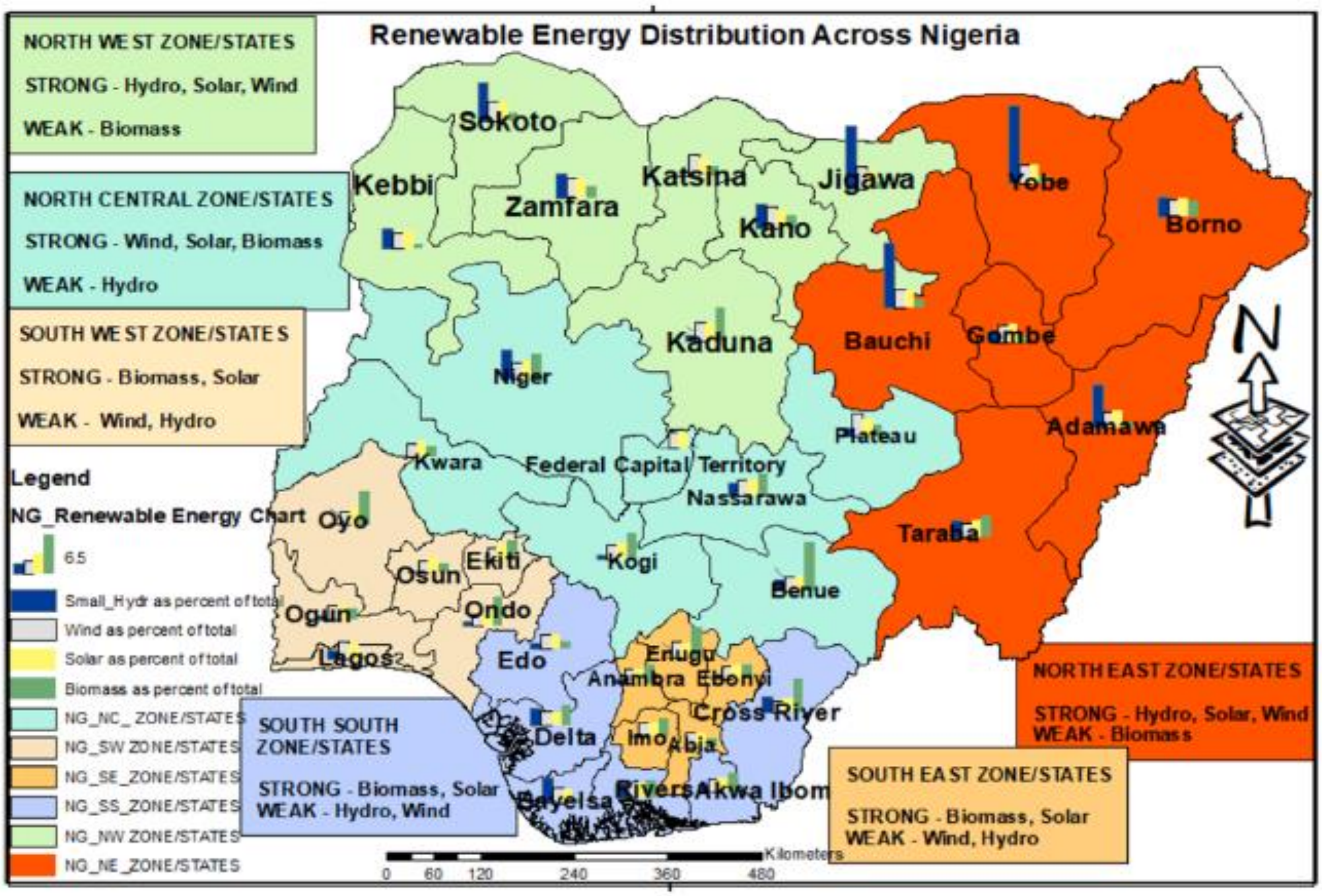

Figure 4: Renewable energy landscape in Nigeria (Okedu et al., 2024b)

This map, which was adapted by Okedu et al. (2024b), highlights the abundance of renewable energy based on region. In northern states, including Sokoto, Kebbi, Zamfara, Katsina, Jigawa, Kaduna, and Plateau, wind energy is also feasible, whereas hydropower is well-fitted in central states, with abundant riverbeds, among them Niger, Kwara, Kogi, Nasarawa, and Benue (Okedu et al., 2024b; Adoghe et al., 2023). States in the southwest and south-

south, such as Oyo, Osun, Ondo, Edo, Delta, Bayelsa, Rivers, Imo, Abia, and Akwa Ibom use hybrid hydro/steam, presumably a mix of water resources with thermal energy sources. The northeastern states of Borno, Yobe, Bauchi, Gombe, and Adamawa have high levels of solar irradiance, which makes them suitable in developing solar energy. Moreover, in the same vein, Taraba State has achieved an advantage in utilizing a hybrid of solar and wind, and instead maximized its own renewed resources towards better energy provision. In spite of this prospectus, renewable sources are not fully exploited, and they provide less than 20 percent of the electricity, primarily on big hydro (Eweka et al., 2022; Oyedepo, 2014). At present, roughly 80 percent of the energy consumed in the country is fossil-based, yet the transition to renewable sources is also a possible and more sustainable option (Ohunakin et al., 2014; Oyedepo, 2014). Renewable energy adoption has not developed because of the continued gap in funding, poor policy enforcement, and flawed institutional backing (Adeshina et al., 2024; Ogbodo-Nathaniel et al., 2024). The renewable energy situation in Nigeria is paradoxical, with enormous reserves of sunlight, wind, biomass, and hydropower going unexploited, despite the increase in energy demand. To a great extent, this underdevelopment is due to infrastructural inadequacies, poor regulatory systems, and riskiness of investment. In summary, as can be seen in Table 2, the limitations to the uptake of renewable energy are accompanied with explicit prospects of transformational learning, especially in areas that have good climatic and geographical factors. This kind of synthesis highlights the importance of coherent policy and investment approaches to unlock the renewable potential of the country.

Table 2: Renewable Energy Potentials, Current use, Barriers, and Opportunities in Nigeria

Resource	Estimated Potential	Current Use	Barriers	Opportunities	Reference
Solar	Avg. GHI 1,600–2,200 kWh/m²/yr; technical PV potential ≈210 GW (using 1% of land area)	<1% of grid electricity; ~37 MW utility PV connected	High upfront costs, weak grid, policy uncertainty	Abundant resource; rural mini-grids; falling PV costs; private sector interest	IRENA (2023); Trade.gov (2022)
Wind	~3.2 GW onshore (technical, 1% land-use scenario); best sites in north & coastal areas	<1% of generation; only a few pilot projects (e.g., Katsina 10 MW, incomplete)	Poor wind data; lack of investment; limited transmission in resource-rich areas	Hybrid solar–wind systems; off-grid rural electrification	IRENA (2023); AfDB (2022)
Large Hydropower	Theoretical ≈24 GW; exploitable ≈14 GW	Installed ~1.9–2.1 GW (Kainji 760 MW, Jebba 578 MW, Shiroro 600 MW); contributes ~24% of generation	Aging infrastructure, siltation, seasonal flow variability	Plant rehabilitation (Kainji/Jebba AfDB project); expansion of medium hydro	AfDB (2022); IRENA (2023)
Small Hydropower (SHP)	~3.5 GW across ≈278 identified sites (national estimate); subset ~734 MW	<100 MW exploited	Funding gaps; weak local capacity; policy fragmentation	Rural electrification; ArcGIS-based site mapping; socio-	IRENA (2023) Fasipe et al. (2021)

	surveyed in some states			economic development	
Biomass	~43% of Nigeria's primary energy supply from biomass (firewood, charcoal, residues); large potential in agricultural waste	Predominantly traditional use (cooking/heating); limited modern bioenergy projects	Inefficient traditional use; deforestation; lack of conversion tech	Waste-to-energy; modern bio-digesters; job creation in rural economy	IRENA (2023); IEA (2023)

3.1. Solar Energy

The solar energy potential in Nigeria is among the most significant in the world where the average daily solar insolation is 5.5 kWh/m², and 7.0 kWh/m 2 in the north (Dinneya-Onuoha, 2025; Ohunakin et al., 2014). The country is in the tropics, and it is a promising location to get renewable energy due to the large amount of solar radiation (Ogunjo et al., 2021; Agbo et al., 2023). Solar energy can be tapped using several technologies such as photovoltaic (PV) systems and solar thermal energy technologies (Ohunakin et al., 2014; Bello et al., 2024). Nigeria has an underdeveloped energy sector that is currently very dependent on fossil fuels, yet renewable energy sources, such as solar energy, provide a sustainable solution (Kashyap et al., 2022; Ogbonnaya et al., 2019; Adoghe et al., 2023). Solar energy can be integrated to improve voltage stability and act as an alternative to shunt reactors on the national grid (Adetokun et al., 2021). The installed solar energy sector capacity in Nigeria is about 112 MW, and off-grid solutions have enhanced access to energy in rural locations (Nkalo, 2025). Northern Nigeria, especially, is richly endowed with solar energy, and thus, it is perfect in solar energy integration (Gideon & Mong'are, 2024). Obstacles are listed as policy discontinuity, capital cost, and grid integration (Perera et al., 2019; Abdullahi et al., 2022). Solar system like Slater solar has the potential to produce over 400 GW of energy that would supply all the energy needs of Nigeria (Ozoegwu et al., 2017).

3.2. Wind Energy

Nigeria is highly promising in wind energy, but its development is still low because of technical, policy, and socio-economic factors (Ogunniyi et al., 2024; Francis & Usman, 2024). It has been observed that wind resources are not homogeneously distributed; the most promising ones are found in northern territories, mountainous regions, and coastal areas (Akporhonor et al., 2023; Adedipe et al., 2018; Adoghe et al., 2023). The mean speed of wind flows is 2-9.5 m/s with power densities of 3.4-520 kW/m 2, which presents significant potential to generate energy using the right technology (Adaramola and Oyewola, 2011). Northern part of the country; it is the most promising area as the average speed of wind is 2.64 to 9.83 m/s a month (Ohunakin et al., 2011). The central target areas that will show long-term wind power density include Katsina and Kano, and Kaduna that will be good to implement large-scale wind power projects (Francis & Usman, 2024). The power density and the average wind speed in Enugu, southeastern Nigeria, is 96.98 W/m 2 and 5.42 m/s with Owerri and Onitsha recording lower results (Oyedepo et al., 2012b). In other regions, such as Ota in Ogun State have been researched as area wind evaluations (Akinpelu et al., 2019).

Although this is possible, there are various impediments that limit the development of wind energy. Investor confidence is curtailed by policy and regulatory uncertainties, fragile implementation frameworks and frequent changes in legislation (Ajia, 2025; Adedokun et al., 2023). The lack of awareness and security threats are socio-cultural obstacles that hinder further development (Adedokun et al., 2023). High capital costs, inefficient tariffs, unfavorable market structures, and bureaucratic inefficiencies and overlapping institutional mandates reduce investment, and slow project implementation (Somoye, 2023; Adedokun et al., 2023). Integration into the national grid is prevented by technical and infrastructural constraints such as failing transmission networks and insufficient energy storage (Adedokun et al., 2023). The federal government has promised to expand renewable energy that would facilitate the development of wind energy (Idris et al., 2020). But to achieve the potential of using wind energy in Nigeria, it is necessary to have consistent policies, clear guidelines on implementation, firm government dedication, and effective economic incentives to draw in private investment (Ogunniyi et al., 2024; Idris et al., 2020).

3.3. Hydropower

Hydropower is the most developed source of renewable energy in Nigeria (although minor power plants are also present), so far, the largest power plant constituted the backbone of generation capacity, including Kainji, Jebba, and Shiroro, yet out of the estimated 12.5 GW of installed hydropower capacity in the country, only 2.3 GW are currently operational due to infrastructural decay and seasonal fluctuations in flows (Eweka et al., 2022; Oyedepo, 2014). In addition to huge facilities, Nigeria has significant hydropower reserves which are not fully exploited and are widely distributed among the rivers basins, including Niger and Benue (Yuguda et al., 2023; Oyinna et al., 2023; Cyprain & Abass, 2025; Amogu, 2022; Sanni, 2018; Ohunakin et al., 2011). Small hydropower (SHP) resources (3.5 GW, 278 sites) are unexploited yet have the potential to deliver a reliable supply of electricity to rural and underserved regions (Brimmo et al., 2017; Ugwu et al., 2022; Amogu, 2022; Ebhota & Tabakov, 2018). Recent works using GIS, remote sensing, and hydrological models identified feasible SHP locations, especially in Borno, Niger, Edo, Anambra, and Jigawa states (Fasipe et al., 2021; Oyinna et al., 2023), and mathematical and computational models were used to predict plant capacities and conversion efficiencies (Adejumobi et al., 2007). However, technical barriers, high capital costs, weak policy frameworks, environmental, and social risk limit development (Ogbo et al., 2024; Adeshina et al., 2024; Ajia, 2025; Pranoto et al., 2025). Some methods to address them involve policy adjustments, economic incentives, technological development, incorporating communities, and linking it with solar and wind power by using hybrid systems (Ajia, 2025; Adeshina et al., 2024; Liu et al., 2025; Agwu et al., 2023; Ogunjo et al., 2023). The future focus is on sophisticated spatial and hydrological resource analyses, in-depth feasibility studies, hydrokinetic turbine development, and legal and institutional strengthening (Fasipe et al., 2021; Ladokun et al., 2018; Ogbodo-Nathaniel et al., 2024), which would help Nigeria to unlock its hydropower potential in terms of sustainable electrification, economic growth, and environmental resistance.

3.4. Biomass and Bioenergy

Nigeria is blessed with rich biomass reserves that can be utilized to create energy. Agricultural sector is large in the country and the agricultural residues like rice husks, corn stalks and sugarcane bagasse are readily available (Ajoku, 2011). Other biomass sources comprise forest residues (wood waste and sawdust) (Ajoku, 2011; Okedu et al., 2024a). There is also another possible bioenergy feedstock, MSW, which can be transformed via incineration, gasification, or anaerobic digestion (Adekanye, 2025; Yusuf et al., 2019). Crop residues alone can be significantly big in potential, which can serve the regional heat and electricity demand (Azasi et al., 2020). With an approximate daily production of 227,500 tonnes, animal manure has great biogas generation potential, especially in rural farming communities (Godfrey, 2024). Overall, agricultural residues in Nigeria, as well as municipal waste, measure approximately 130 million tonnes of residues annually, and they could produce an estimated 12.8 terawatt-hours (TWh) of electricity (Giwa et al., 2017; Jekayinifa et al., 2020). The consumption of conventional biomass (firewood, charcoal) currently satisfies almost 70 percent of household demand, yet it has raised the issue of deforestation and indoor air pollution that poses extreme health hazards (Shaaban and Petinrin, 2014; Khattra et al., 2024). Biomass can be converted into useful energy using several technologies. Even though combustion remains a widespread way of heat and power production, it can also produce greenhouse gases under bad management (Okafor et al., 2022). The concept of gasification, which is a highly sophisticated thermal treatment process, converts biomass into gas, which will be utilized in internal combustion engines or gas turbines (Babatunde et al., 2019; Sobamowo & Ojolo, 2018). Biological Ananerobic digestion converts organic matter into a biogas of methane and carbon dioxide that can be used to heat or cook or produce electricity (Ezealigo et al., 2021; Okonkwo et al., 2018). Pyrolysis is a thermal decomposition process of biomass by which bio-oil, biochar, and syngas are obtained, which can be further included in the fuels and chemicals (Ezealigo et al., 2021). Modern biomass solutions, including biogas digesters and waste-to-energy facilities, would be drastically beneficial to the energy distribution in Nigeria. These technologies can serve up to 50 million homes. Adopting bioenergy as an energy in Nigeria can bring several advantages such as less dependence on fossil fuels, less emission of greenhouse gases, and better access to energy, especially in rural communities (Mohammed et al., 2013; Mohammed et al., 2014). Technological development also leads to the production of bioenergy that boosts local economies through the generation of job opportunities in biomass production, harvesting as well as bio-processing (Okoro et al., 2024). Nonetheless, there are multiple obstacles that deter the mass-scale adoption of bioenergy. The use of unsustainable biomass and improper management of resources also leads to environmental degradation and health hazards (Okoro et al., 2024; Orifah et al., 2018). Poor infrastructure, lack of financial resources, and unreliable government policies (Somoye, 2023; Ajia, 2025) have been identified as other developmental barriers. Furthermore, the bioenergy business is also void of sufficient information about the availability of resources, which prevents proper planning and investing (Ezealigo et al., 2021).

3.5. Geothermal and Emerging Sources

Geothermal in Nigeria is still not exploited on a large scale but has enormous potential, especially on the Benue Trough and parts of the Rift Valley. In these areas, the temperature in the underground reaches between 200 and 230 C within a depth of five kilometers, which can be used directly in the heat production as well as in the production of electricity (Okolie et al., 2019). It is estimated that the geothermal potential would be around 2.5 GW to serve industrial heating and grid-based power demand. Other emerging energy technologies, other than geothermal, provide locally manageable power generation. The Niger Delta tidal energy has a potential estimated at under 1 MW, whereas triboelectric nanogenerators are at the experimental phases and could be used at small-scale levels (Cyprain & Abbas, 2025, Trinh & Chung, 2024). A combination of factors constrain exploitation of these resources, including insufficient exploration data, drilling and infrastructure cost, and the absence of well-developed regulatory measures to guide investment and operation (Okolie et al., 2019). These challenges notwithstanding, the potential of geothermal and other emerging forms of energy can be realized through targeted research, policy support, and pilot projects to help in the diversification of renewable energy in Nigeria.

4. CHALLENGES TO SUSTAINABLE ENERGY TRANSITION

The implementation of renewable energy in Nigeria to a sustainable system continues to experience bottlenecks in spite of the potential of this country in terms of renewable energy. Such difficulties are interrelated and grouped into five essential categories.

4.1. Policy and Regulatory Barriers

Policy frameworks in the energy sector are weak and inconsistent in Nigeria. Institutional fragmentation and postponement of the implementation of projects through overlapping mandates of over 30 agencies such as Rural Electrification Agency (REA), Nigerian Electricity Regulatory Commission, and Nigerian National Petroleum Company (NNPC) are the challenge (Adeshina et al., 2024; Lawal, 2021). Alterations in policy and regular changes in regulations demoralize investors, and inadequate enforcement systems hamper the proper implementation of good-intended policies like the National Energy Policy and the Renewable Energy Master Plan (Adedokun et al., 2023; Edomah, 2016).

4.2. Financing and Investment Constraints

In Nigeria, renewable energy projects are plagued with underfunding. The restriction on capital flow is caused by limited access to long-term financing, elevated interest rates, and risk-averse investors (Asemota & Olokoyo, 2022; Upaa et al., 2024). Public-private partnership models are inadequately developed, and the estimated annual fossil fuel subsidies of \$3.8 billion pervert the market by deterring renewable investment (Adedokun et al., 2023). Further, there is ambiguity on security threats, ineffective land tenure, and foreign exchange instability (Mungai et al., 2022).

4.3. Technological and Capacity Gaps

The grid infrastructure of Nigeria is poorly designed to accommodate variable sources of renewable energy. The barrier to renewable uptake is frequent instability and relatively low storage capacity (less than 50 MW) (Sachan et al., 2022; Ohunakin et al., 2014). Another energy sector area lacking human capital is that less than 15% of engineers in the energy sector are specially trained in renewable energy technologies, and local universities do not generate many applications of research (Avwioroko, 2023; Olajiga et al., 2024). The level of research and development expenditure is 0.3 percent of GDP, which is significantly lower than those of the emerging economies (Bhuiyan et al., 2022).

4.4. Environmental and Social Concerns

Large-scale energy projects and megafacilities may contribute to land-use issues, population displacement, and inadequate compensations which trigger community resistance. To assert an example, the planned Mambilla hydropower project has been postponed because of the protests by locals (Agwu et al., 2023). Solar farms overshadow agricultural land, and food security is a concern. Moreover, the unregulated import of inexpensive solar modules has disposed of an estimated 12,000 tonnes of toxic e-waste per year, which is sometimes recycled without controls, introducing dangerous substances into the water systems (Barau et al., 2020; Segovia-Hernandez et al., 2023). In the meantime, the use of diesel-powered generators (approximately 40 GW worth) anchors high emissions (around 29 million tonnes of CO_2 each year) and adds to about 28,000 premature deaths due to air pollution (Edomah, 2016; Ulpiani et al., 2024).

4.5. Infrastructure Deficits

The archaic and weak infrastructure in Nigeria is also a significant impediment. The average transmission losses are 40 or the same as 1.4 billion yearly, and rural connectivity is one-quarter (Emodi and Boo, 2015). Opportunities of mini-grids are at over 10,000 identified locations, yet they do not supply than 5 percent of demand (Namujju et al., 2023). The systemic inefficiencies such as reliance on imported materials, choked ports, and ineffective rural roads raise project expenses and set-backs (Abdullahi et al., 2017; Razmjoo et al., 2024). Renewable energy its adoption will be limited without significant modernization including increasing grid capacity, storage integration, and the enhancement of logistics (Adedokun et al., 2023).

5. POLICY AND INSTITUTIONAL FRAMEWORK

Nigeria has set a number of policies and institutions to ensure sustainable energy development. These structures have been indicative of ambition but have been negated by poor implementation, overlapping of policies, and insufficient institutional capacity.

5.1. National Policy Frameworks and Policy Gaps

Over the last two decades, Nigeria has introduced a series of policies to drive its energy transition, but progress on the ground has consistently lagged behind expectations. The National Energy Policy (NEP) of 2003 was an early attempt to diversify the energy mix and encourage the use of renewables. However, the lack of clear implementation strategies and accountability meant its impact was minimal (Oyedepo, 2014; Edomah, 2016). A more ambitious effort followed with the Renewable Energy Master Plan (REMP), launched in 2005 and revised in 2012, which set targets of achieving 23% renewable electricity by 2025 and 36% by 2030. In practice, though, renewable penetration has stayed below 20%, underscoring the gap between vision and reality (Akuru & Okoro, 2014; Adeshina et al., 2024). The National Renewable Energy and Energy Efficiency Policy (NREEEP) of 2015 sought to accelerate progress by promoting clean energy, efficiency, and private sector investment, but it struggled with limited funding, overlapping institutional roles, and weak monitoring (Lawal, 2021). Most recently, the Energy Transition Plan (ETP) of 2023 has laid out the boldest vision so far, committing Nigeria to net-zero emissions by 2060, scaling solar capacity to 30 GW by 2030, and attracting an estimated $410 billion in investment (Olanrele, 2023; Adedokun et al., 2023).

Yet, despite these frameworks, familiar challenges continue to hold back progress. The division of responsibilities across multiple agencies often leads to duplication and inefficiency. Political influence and frequent changes in leadership disrupt continuity, making it difficult to sustain long-term initiatives. Funding remains inadequate, limiting the scale of renewable projects, and weak accountability and monitoring systems reduce the likelihood that targets will be achieved. Together, these gaps reveal how governance and financial barriers continue to undermine Nigeria's renewable energy transition, even in the face of increasingly ambitious policy commitments.

5.2. Institutional Roles

i. Nigerian Electricity Regulatory Commission (NERC): Supervises licensing and tariffs and grid codes. Though regulatory understanding has become more evident, regulation has minimal enforcement capacity, and political meddling continues (Adoghe et al., 2023).
ii. Rural Electrification Agency (REA): Deploys off-grid and mini-grids, such as the Nigeria Electrification Project (NEP). REA has helped with development in mini-grids and home solar, yet coverage is considerably lower than demand.
iii. Nigerian Bulk Electricity Trading Company (NBET): Plays an intermediate role between generators and the distributors. Liquidity difficulties and delays in the receipt of payment reduce investor confidence (Adedokun et al., 2023).
iv. Energy Commission of Nigeria (ECN): Directs policy planning and coordination. Nonetheless, the presence of overlapping functions with the Ministry of power and other state bodies interfere with effectiveness (Edomah, 2016).

5.3. International and Regional Cooperation

Nigeria is engaged in several international and regional initiatives that aim to strengthen its renewable energy transition and expand access to clean power. Under the Paris Agreement, ratified in 2016, the country pledged to reduce greenhouse gas emissions by 20% unconditionally and up to 45% with international support by 2030. It also participates in the African Development Bank's Desert-to-Power Initiative, which seeks to deploy 10 GW of solar capacity across the Sahel region, including Nigeria (Mungai et al., 2022). At the national level, the World Bank's $350 million Nigeria Electrification Project has supported solar mini-grids and off-grid home systems, while the USAID-led Power Africa program provides technical expertise and financial support to encourage private sector participation in clean energy projects. These partnerships bring essential financing, technology, and knowledge transfer, but their effectiveness is often limited by misalignment with Nigeria's domestic policy priorities and delays caused by bureaucratic bottlenecks (Adeshina et al., 2024).

6. KEY PROJECTS AND INITIATIVES

Nigeria has initiated massive programs and projects in an effort to close the access gap to energy. Government, international donors, community-led organizations and private investors support these types of initiatives. Though this has been achieved, scale-up is still limited due to, among other things, financing, governmental, and infrastructural issues.

6.1. Government-led Programs

Nigeria has launched several government-led programs in collaboration with international partners to accelerate renewable energy deployment and expand electricity access. The Solar Power Naija program, introduced in 2020, set out to deliver five million solar connections to reach approximately 25 million people, with a strong focus on rural communities. However, progress has been slow, with less than 10% of the target achieved by 2024 (Olanrele, 2023). Similarly, the Nigeria Electrification Project (NEP), a $350 million initiative supported by the World Bank and the African Development Bank and implemented through the Rural Electrification Agency (REA), seeks to promote mini-grids, solar home systems, and other productive uses of energy to improve access in underserved areas. Nigeria is also a participant in the Sustainable Energy for All (SE4All) initiative, through which it has committed to achieving universal energy access by 2030. Yet, progress remains off-track, reflecting broader implementation challenges that have consistently constrained national energy access programs (Edomah, 2016).

6.2. Private-Sector Initiatives

The individuals firms have now become the centre stage of renewable off-grid development. Other companies, such as GVE Projects, Lumina Solar, or Lumos, have deployed thousands of mini-grids of solar platform and home units, which serve over one million households (Adoghe et al., 2023; Nkalo, 2025). The Pay-as-you-go (PAYG) models have very low restrictions to afford and that a household can receive solar power with payment cost below of 10/month fees (Upaa et al., 2024). There is also electricity generation by independent Power Producers (IPPs) that provides electricity to industrial clusters and estates without passing through unproductive distributed companies (Lawal, 2021).

6.3. International Support Programs

In addition to domestic initiatives, Nigeria benefits from several international programs that provide financial and technical support for renewable energy expansion. The World Bank and the African Development Bank (AfDB) play a central role in financing projects such as the Nigeria Electrification Project (NEP), the Desert-to-Power Initiative, and the expansion of mini-grids across underserved regions (Mungai et al., 2022). The USAID-led Power Africa initiative also contributes technical expertise and financial assistance, particularly in promoting community-driven and private sector-led renewable energy projects (Adeshina et al., 2024). Furthermore, the Global Environment Facility (GEF) has supported pilot projects in southern Nigeria, including biomass and waste-to-energy plants (Giwa et al., 2017). While these programs provide critical resources, knowledge transfer, and capacity-building, their overall impact has often been constrained by bureaucratic bottlenecks, delays in fund disbursement, and persistent local implementation challenges (Adedokun et al., 2023).

6.4. Community-based and Civil Society Initiatives

Community-based and civil society initiatives are playing an increasingly important role in addressing energy poverty, particularly in rural areas where access to grid electricity remains limited. Cooperative mini-grids, often based on small solar or hydro systems, are operated and maintained by local cooperatives, frequently with the support of non-governmental organizations (NGOs). These systems tend to be more sustainable when ownership and management are rooted within the community itself. NGOs such as the Clean Technology Hub have also been instrumental in advancing renewable energy adoption by conducting awareness campaigns, piloting projects, and fostering local capacity (Sobajo, 2024). In addition, community-level productive-use applications such as solar-powered irrigation systems and solar milling machines are enhancing agricultural productivity and contributing to socio-economic development in rural societies (Gideon & Mong'are, 2024). While these grassroots initiatives often succeed in fostering local ownership and ensuring direct socio-economic benefits, they are frequently constrained by limited financing, technical capacity, and scalability challenges. As such, their long-term effectiveness depends on stronger integration with national frameworks and greater institutional support to expand their reach and sustainability.

7. TECHNOLOGICAL AND RESEARCH TRENDS

The energy transition in Nigeria is revolved around technological innovation. In spite of the fact that the industry is still limited by the lack of infrastructure development and unsatisfactory research and development, there are encouraging signs of the sustainability of electrification in the recent developments.

7.1. Off-Grid and Mini-Grid Systems

Small-scale off-grid systems, especially solar mini-grids and stand-alone systems, have grown exponentially in rural Nigeria. There is a growing adoption of hybrid configurations solar-diesel-battery to enhance reliability and decrease costs (Oseni, 2012b; Adedipe et al., 2018). As of 2024, mini-grids serve about 3 million Nigerians, with potential to reach more than 40 million by 2030 (Nkalo, 2025). Their success is supported by declining photovoltaic costs, digital payment systems, and donor-backed financing models such as pay-as-you-go (PAYG) schemes (Upaa et al., 2024).

7.2. Smart Grids and Energy Storage

The modernization of the grid is urgent to incorporate variable renewable energy sources. Lower-scale pilot projects utilizing smart meters, Internet of Things (IoT) instrumentation, and artificial intelligence in the management of demand have been implemented in Lagos and Abuja (Adoghe et al., 2023). Storage capacity has not reached 50 MW countrywide yet, but lithium-ion battery can be tested over mini-grids and industrial clusters (Sachan et al., 2022). Increased storage technologies, paired with flexible generation, will be required to offset a high-renewable system of the future in Nigeria (Herbert, 2021).

7.3. Equipment and Material Innovation

Renewable industry depends on equipment mostly imported, which increases the expense and risk of the supply chain (Razmjoo et al., 2024). They are also working on localized production, such as solar panel assembly in Lagos and Kano (Asemota and Olokoyo, 2022). New bifacial solar modules, perovskite cells, and cheap biogas digesters are also being tested in universities and startups, with little progress in commercialization (Babatunde et al., 2019; Avwioroko, 2023).

7.4. Local Research and Development

Nigerian higher education and research centers are making their contribution in the form of solar dryers, micro wind turbines, and better cookstoves (Jekayinifa et al., 2020; Olajiga et al., 2024). Nevertheless, funding (0.3% of GDP spent on R&D) is insufficient, industry cooperation is absent, and patents are not advanced, which inhibit scales (Bhuiyan et al., 2022). Academia, industry and government should work hand in hand to bring research into market solutions (Cyprian & Abbas, 2025).

7.5. Outlook

Technological progress in Nigeria is uneven but promising. Off-grid solutions are leading adoption, smart grids and storage are emerging, and local R&D is building capacity. Scaling these innovations requires stronger financing, regulatory support, and knowledge transfer.

8. STRATEGIC PATHWAYS AND RECOMMENDATIONS

Sustainable energy transition in Nigeria needs systemic reforms to solve systemic weaknesses and capitalize on the renewable resources in the country. Following the evaluation of present position, difficulties, and plans, there are five strategic pathways that are suggested.

8.1. Policy and Governance

Integrate diffuse policy structures by bringing together overlapping agencies and expressing the role and definition of the institutions (Adeshina et al., 2024; Edomah, 2016). Create a unified and empowered energy transition authority to harmonize plans, projects and oversight, between ministries and agencies. Improve compliance with renewable energy ambitions on the Renewable Energy Master Plan and the Transition to Energy Plan and add a transparent reporting system (Lawal, 2021).

8.2. Financing and Investment

Restructure fossil fuel subsidies, which now encourage the implementation of renewable energy, and shift a portion toward clean energy (Adedokun et al., 2023). Grow blended finance to bundle together government capital, funds and donor capital to de-risk renewable projects (Mungai et al., 2022). Encourage green bonds, carbon credits, and concessional financing of large-scale solar and wind energy projects (Asemota & Olokoyo, 2022). Enhance the role of local financial institutions in delivering credit to small-scale renewable projects, such as pay-as-you-go systems (Upaa et al., 2024).

8.3. Technology and Infrastructure.

Modernize grid infrastructure to minimize losses, add renewables, and enhance resilience (Oyedepo, 2014; Sachan et al., 2022). Scale battery storage, as well as hybrid systems, to stabilize the supply both in a grid and off-grid setting (Herbert, 2021). Promote the local production of renewable energy-related technologies to decrease reliance on imports and create industrial capacity (Razmjoo et al., 2024). Adopt new digital technologies, including smart meters and demand management based on artificial intelligence, to optimize the system (Adoghe et al., 2023).

8.4. Human Capital Development

Enlarge vocational training opportunities and higher education programs dedicated to renewable energy engineering, project management and entrepreneurhip (Avwioroko, 2023; Olajiga et al., 2024). Form collaborations between academia, business, and government in applied research and commercialization (Bhuiyan et al., 2022). Promote gender equality in the training and work in the field of energy, as women are overrepresented in energy poverty situations (Ohunakin, 2010).

8.5. Community Education and Outreach.

Conduct countrywide awareness of the advantages of clean energy and press against opposition to new developments (Sobajo, 2024). Privatize renewable energy systems by involving communities in the planning and owning of systems to achieve better acceptability and sustainability. Empower the civil society and other non-governmental organizations (NGOs) to encourage practices of behavior change and energy efficiency at the individual and community level (Gideon and Mong'are, 2024).

9. CONCLUSION

The energy paradox that Nigeria continues to experience despite having large reserves of energy is connected to poor governance, funding issues and gridlock of infrastructure. However, the nation has large potential of renewable energy in various areas. Rural electrification can be fueled by solar and biomass, grids can be more reliable and operated by hydropower, and wind appends an opportunity in the north and coastal areas. New resources such as geothermal and tidal power are promising potential niche and localized use. In order to achieve this potential, Nigeria needs to undertake concerted reforms: to have unified and solid policy frameworks, to rationalize subsidies, reinforce investment incentives, to encourage local innovation in renewable technologies, and to have an inclusive stakeholder involvement. Today, sector-specific solutions like scaling mini-grids, modernizing biomass conversion, and increasing wind and solar installation in high potential areas will also be instrumental. Nigeria has the potential to not only meet universal energy access targets and climate targets, but it can become a clean energy pioneer on the continent as well with coherent governance, strategic investment, and daunting implementation, showing how resource-rich developing countries can leap to a sustainable energy future.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this review.

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