

## **ACCESS TO LOW-CARBON ENERGY TECHNOLOGIES IN NIGERIA: STATUS AND CHALLENGES**

**Babatunde. A. Aodu<sup>1,4</sup>, Maruf Sanni<sup>1,2\*</sup> and Y.O. Akinwale<sup>3</sup>**

<sup>1</sup>*National Centre for Technology Management, Federal Ministry of Innovation, Science, and  
Technology, Obafemi Awolowo University, Ile Ife, Nigeria*

<sup>2</sup>*RFF-CMCC European Institute on Economics and the Environment, Centro  
Euro-Mediterraneosui Cambiamenti Climatici, c/o BASE Via Bergognone 34, Milano 20144, Italy*

<sup>3</sup>*Imam Abdulrahman Bin Faisal University, Dammam, Saudi Arabia.*

<sup>4</sup>*African Institute for Science Policy and Innovation (AISPI), Obafemi Awolowo University, Ile Ife,  
Nigeria*

*\*Corresponding author email: maruf.sanni@nacetem.gov.ng*

*Maruf Sanni <http://orcid.org/0000-0001-8313-9910>*

*Babatunde Adetunji Aodu: <https://orcid.org/0009-0001-6065-1046>*

*Yusuf Opeyemi Akinwale <https://orcid.org/0000-0003-3955-2606>*

### **Abstract**

*Nigeria possesses vast low-carbon energy resources, such as solar, wind, biomass, hydro, and geothermal power. Despite this, the country struggles to ensure a stable electricity supply and widespread energy access. The adoption of low-carbon energy technologies is widely recognized as essential for economic growth and social progress. This study explores the enabling and limiting factors affecting the adoption of low-carbon energy technologies in Nigeria, the variety of renewable energy sources available, and the policies and regulations aimed at ensuring sustainable energy access. By reviewing relevant literature (2018–2025) on renewable and/or low-carbon energy technologies, with a focus on Nigeria; the study identifies key influences on sustainable energy access. The findings reveal that multiple interconnected factors, such as policy and regulatory frameworks, grid expansion costs, economic barriers, peer-to-peer (P2P) energy trading, investment risks, pricing models, socio-cultural dynamics, technical limitations, poor maintenance, abandoned projects, and a lack of skilled personnel, play a crucial role. The paper concludes with highlights of important policy implications, stressing the necessity of tailored incentives for specific low-carbon energy pathways. Additionally, it advocates pro-poor strategies and expanded energy access to reduce inequality and combat energy poverty in Nigeria.*

**Keywords:** *Low-Carbon Energy Technologies, Energy Access, Barriers, Rural Areas, Nigeria*

### **1.0 Introduction**

The consequences of global warming and climate change are deeply felt worldwide, threatening the welfare of future generations and demanding immediate international action. According to the IPCC-2021 report, failing to drastically reduce CO<sup>2</sup> and other GHG emissions will likely result in global temperatures exceeding the 2°C limit before the end of the 21st century (Cohen *et al.*,

2022). The United Nations' 2030 Sustainable Development Goals (SDGs) highlight the critical need for swift climate action (Yetano Roche *et al.*, 2020). Key strategies include expanding access to renewable energy, supporting sustainable economic development, and promoting eco-friendly consumption and production while balancing economic, social, and environmental priorities to ensure inclusive progress (Yusuf, 2023).

The transition to clean, reliable, and sustainable energy is a key priority for inclusive development worldwide (Gu, Renwick, & Xue, 2018). For nations like Nigeria, with fast-growing populations and expanding socioeconomic demands, ensuring widespread access to affordable and clean energy is crucial (Ofori, Gbolonyo, & Ojong, 2023). According to the International Energy Agency (IEA, 2020), energy access means households can reliably and affordably obtain both clean cooking solutions and sufficient energy to meet basic needs. This access plays a vital role in reducing poverty, improving public health, boosting productivity, fostering market competition, and supporting equitable economic growth (Zhao *et al.*, 2023).

Although some progress has been made in sustainable energy development, many developing nations still grapple with acute energy deficits. Even connected households often experience intermittent supply, receiving power for only a few hours daily. Urban centres typically benefit from better grid coverage, while rural communities encounter far more severe energy deprivation (Emezirinwune *et al.*, 2024). World Bank development indicators reveal that 66.9% of Nigeria's rural population lacked electricity access in 2020 (Olanrele *et al.*, 2020). Notably, electricity access varies dramatically across Nigeria's 36 states. Lagos State enjoys near-universal coverage at 99.3%, while Taraba State struggles with a mere 10.9% access rate (Akpan, 2015). This imbalance arises due to some factors, notably the affordability of electricity, differences in state population densities, and the uneven distribution of transmission infrastructure. In contrast, the Northeast remains severely underserved due to its scarcity of generation facilities and transmission networks. Despite having an installed capacity of 15,000 MW, Nigeria's actual electricity generation hovers between just 3,500 and 5,000 MW, highlighting a critical supply gap (Ikemba *et al.*, 2024).

Low-carbon energy solutions for electricity access can be broadly classified into two approaches: centralized grid expansion and decentralized systems (including mini-grids and standalone installations). Mini-grids and standalone systems are proving particularly viable for remote areas where grid expansion would be prohibitively expensive, technically challenging, or result in inefficient energy distribution (Zebra *et al.*, 2021; Duran & Sahinyazan, 2021). Grid expansion remains economically justified when targeting high-density urban populations with greater payment capacity, as the scale benefits can offset implementation costs (Ortega-Arriaga *et al.*, 2021).

Existing research has typically examined these sustainable energy resources in isolation or limited combinations, lacking a holistic perspective on Nigeria's complete energy ecosystem. This has created a significant knowledge gap regarding comprehensive assessments of the status and challenges of low-carbon energy technology access in Nigeria, particularly concerning market penetration, viable business models, technological advancements, and the development of supportive policy frameworks. A more integrated analysis is needed to fully understand and leverage the country's renewable energy potential.

This study analyses multiple low-carbon energy technologies capable of improving clean energy access in Nigeria, while proposing policy recommendations to enhance sustainable energy adoption nationwide. The research is organized systematically: Section 2.0 explores the energy

landscape and key energy needs in Nigeria; Section 3.0 examines the low-carbon energy potential and its utilization; Section 4.0 analyses recent initiatives on access to low-carbon energy technologies in Nigeria. Section 5.0 discusses barriers to low-carbon energy access in Nigeria, with Section 6.0 providing the conclusions.

## **2.0 The Energy Landscape and Key Energy Needs in Nigeria**

The economic prosperity of a nation significantly relies on the long-term availability of energy from sources that are accessible, affordable, and environmentally friendly (Oyedepo *et al.*, 2018). Meanwhile, energy is also found to have interconnectivity with the fundamental issues facing Sub-Saharan African (SSA) countries such as security, public health and climate change (Akinwale, 2023). Despite the abundance of hydrocarbon resources, more than 71% (approximately 140 million) of Nigerians lack access to modern energy services, including electricity, clean cooking facilities, and modern fuels (World Economic Forum, 2023). In fact, according to a survey conducted by the Nigerian National Bureau of Statistics (NBS), only approximately 18% had access to clean cooking (gas and electric stoves) in 2019 (NBS, 2020). This implies that traditional biomass, which contributes to local air pollution, accounted for the majority of the energy used for cooking in various homes in Nigeria. The traditional biomass is mainly used in the rural areas for heating and cooking, where there are lots of populations with poor access to clean energy and less attention given to environmental issues.

In the power sector, electricity is supplied through on-grid and off-grid systems. Although the overall installed capacity of on-grid-based systems is approximately 13 GW, only approximately 4.5 GW is mostly available during the peak period, largely due to aging and inefficient infrastructure, gas supply issues, operational inefficiencies, and hydrological constraints (Obada *et al.*, 2024). The on-grid system generates electricity from the central system, which consists mainly of natural gas power stations and large hydropower plants with the share of 86% and 14% respectively (Ogundari *et al.*, 2017). There is a great shortage between demand and supply of electricity from the on-grid causing several hours and days of black-outs largely as a result of operational inefficiencies, shortage of gas, seasonal water shortages, transmission and distribution infrastructural challenges, among others (Yetano Roche *et al.*, 2020). This has resulted in many households and companies opting for backup generators which includes mainly self-generating premium motor spirit (PMS) and diesel-powered generators of various sizes depending on the financial capabilities of the individual/companies and the size of their households or offices (Eweka *et al.*, 2022).

The study of Tambari *et al.* (2020) estimated the off-grid fossil fuel-based generating capacity at 30.5 GW, as out of every 10 households connected to the grid, 8.4 have a backup generator while out of 10 companies connected to the grid, 8.6 companies use self-generating fossil-backed generators. In addition to self-generating fossil fuel generators, an off-grid solar-based system has also been recognised as a major means of complementing the on-grid electricity supply (Elinwa *et al.*, 2021). There are various efforts by the Nigerian government to improve the generation, transmission and distribution of electricity to over 200 million people through the on-grid system. The efforts include unbundling the Power Holding Company of Nigeria (PHCN) into 18 companies to improve the efficiency of the electricity service, establishment of Rural Electrification Agency, Rural Electrification Fund and Nigeria Electricity Regulatory Commission; six-year deal with German Siemens AG to increase the power generation capacity to 25 GW and various electrification projects financed by the World Bank and African Development.

Despite all the aforementioned, the current situation has not significantly improved, as many, especially those in the suburbs and rural areas, are still facing many weeks of blackouts, and there is a regular collapse of the national grid (Eweka *et al.*, 2022). This gives room for low-carbon energy alternatives such as solar, wind, biomass, and hydro, which are abundant in Nigeria. Although some of these off-grid alternatives are environmentally friendly, their initial capital expenditure could be slightly expensive. However, transitioning to low-carbon energy sources presents a comprehensive solution to many of the environmental, economic, and social challenges associated with fossil fuel use, paving the way for a sustainable and prosperous future. Many of the low-carbon energy technologies that are in consideration and sought are discussed in the next section.

### **3.0 The Low-carbon Energy Potential and its Utilization**

According to various climate pacts, there is an immediate need to keep the world temperature below 1.5 degrees Celsius (Maizland, 2023) and work towards realizing net-zero emissions by 2050. Since energy is vital in all aspects of life and all sectors of the economy, how this energy is generated, consumed, and disposed of is vital. The Nigerian population is projected to increase from 200 million to 400 million by 2050 (Statista, 2022). If Nigeria's population continues to use traditional biomass and fossil-fuel generators, this population growth could be accompanied by a significant increase in greenhouse gas (GHG) emissions.

The abundant low-carbon energy resources provide a good platform for low-carbon energy technologies, which could be utilized to reduce GHGs and at the same time meet the energy needs of the teeming population of Nigeria. In achieving a low-carbon energy system, there is an urgent need to avoid fossil fuel lock-in in infrastructural investment with long lifespans, such as oil and natural gas pipelines, by diverting new investment towards low-carbon energy infrastructure and at the same time scaling up the existing investment in low-carbon energy.

There are many efforts on the part of the government (such as the Rural Electrification Agency, Energy Commission of Nigeria) and individuals in utilizing solar technologies for street lighting, water pumping in the rural areas, fish drying, refrigerating, cooling, and heating (Olanrele *et al.*, 2020). This has also been explored by schools, hospitals, and water facilities to provide electricity and pump water from their borehole water system (Obada *et al.*, 2024). Furthermore, Sokoto Energy Research Centre (SERC) and the National Centre for Energy Research and Development (NCERD) have undertaken various projects on the application of various solar technologies including water heater, solar crop and fish dryer, solar chicken brooders, solar cookers, water pumping, traffic lighting and lighting of road signs among others. Also, solar PV water pumping for clean potable water was developed by these agencies, such as the 7.2kWp Solar PV Plant at Kwalama in Sokoto, the 2.85kWp Solar PV plant at the Centre for Mentally-Ill Destitute at Itumbuzo in Abia State, and the 5.00kWp Solar PV plant at the Comprehensive Health Centre in Ilaje, Ondo State, Nigeria (Oyedepo *et al.*, 2018).

### **4.0 Recent Initiatives on Access to Low-Carbon Energy Technologies in Nigeria**

Nigeria's ambitious efforts to reduce energy poverty are informed by several national policy reforms, including the National Power Sector Reform Act, Renewable Energy Master Plan, National Water Resources Master Plan (2016-2030), among others. The overarching goal is to channel sustainable pathways that would address the prevailing energy deficit in the country by exploring, harnessing, and integrating the country's natural energy resources potential into the country's energy mix. In this regard, effective and efficient utilization of the low-carbon energy

potential, chiefly, solar, wind, hydro, and natural gas, takes preeminence. Therefore, aggressive investments in low-carbon energy systems to increase energy access and demand are imperative and pertinent.

Consequently, concerted efforts are being made by various stakeholders, particularly, government and private enterprises, towards harnessing the full potential of low-carbon energy technologies for sustainable energy access and economic development in Nigeria. The different approaches employed to achieve and accelerate the development of low-carbon energy technologies in the Nigerian context are:

#### *Solar Powered Energy Initiatives*

In an aggressive and deliberate attempt to improve and increase electricity access to unserved and underserved stakeholders in Nigeria, the Nigerian government embarked on a US\$ 760 million National Electrification Project (NEP) – a US\$ 350 million World Bank Credit facility and US\$ 410 million private sector investments. The project is being implemented by the Rural Electrification Agency, on behalf of the Federal Government of Nigeria. The overarching goal of the project is to implement the largest private investor-driven off-grid electrification project in West Africa using solar PVs. Essentially, the project focused on the provision of affordable and reliable off-grid energy solutions to households, business enterprises (notably, micro-small and medium enterprises – MSMEs), public educational institutions, and public teaching hospitals.

The NEP comprises four components with distinct targets, business, and financial models. The first two components are the provision of solar hybrid mini-grid (US\$ 150 million) and Stand-alone solar home system – SHS (US\$ 75 million) for rural economic development and households/MSMEs (World Bank, 2023, p. 6), respectively. The third component provides a sustainable energy source to selected Federal universities/associated teaching hospitals – ‘Energizing Education’ (US\$ 105 million), and the last component entails technical assistance (US\$ 20 million) (World Bank, 2023, p. 6) concerning operation, maintenance, support infrastructure/framework and towards upscaling the off-grid electrification. Consequently, the off-grid solar market has continued to witness remarkable growth due to the increasing market demand and flexible policy incentives for off-grid solar technology (development) in Nigeria. Noticeably, the market is largely private enterprise-driven. The market is also very complex, particularly concerning the product market target, industry actor composition, and customer value offerings. Nigeria's off-grid solar market presents great and competitive business opportunities for small and large enterprises. These enterprises are either formal or informal by business registration. Usually, the formal off-grid solar enterprise provides complete and tailor-made off-grid solar technologies for residential and commercial purposes.

The mainstream business focus for residential off-grid solar products is Solar Lanterns and Solar Home Systems (including solar lighting expansion kits, fans, and televisions) of various types (in terms of capacity/power rating). Due to the very high initial cost of solar inverter installations, usually unbearable for the vast majority of the Nigerian population, solar inverters are rarely adopted for residential purposes, but are predominantly employed for other business activities and purposes, including production and manufacturing. Notable formal market players in the off-grid solar business in Nigeria include Arnergy, Lumos Nigeria, Solynta, Astrum, SunKing, Rubitec, Solar Force Nigeria, and Novel Solar, among others. The majority of these formal players offer technical support/services (paid or free) in off-grid solar product installation, depending on the type and nature of the technology. In addition, they also assist customers with after-sales support services, including maintenance and repairs/renewal of product components.

More importantly, they offer a flexible payment plan through the pay-as-you-go (PAYG) model. Through the financial model, customers are allowed to make a small down payment, followed by a PAYG of about US\$ 0.15 per day. The PAYG model enhances more inclusiveness, as customers at the bottom of the pyramid (e.g., rural dwellers) who could not afford the ability to pay upfront for the off-grid solar products are sufficiently and adequately considered. On the contrary, the informal enterprise customarily focuses on the provision and repair of off-grid solar components/parts, including panels, batteries, bulbs, and inverters. However, very few segments of the informal business enterprise are also engaged in installation and repair. Generally, the Nigerian off-grid solar market is rapidly evolving with immense potential that will benefit the overall socio-economic wellbeing in the mid-to long-term.

The solar mini-grid (decentralized solar-powered energy system) provides the desired and expected services needed for economic development, growth, and expansion in rural communities that are not connected to the national grid. Furthermore, the stand-alone solar home system (a decentralized solar energy system) serves households/MSMEs with grid connection but is characterized by infrequent and unstable power supply. In addition, a stand-alone solar home system reduces MSMEs' cost burden incurred through alternative fossil fuel energy sources. The Solar Hybrid Mini-grid and Stand-alone Solar Home Systems are principally funded, operated, and maintained by private investors; however, these private investors are supported by different incentive mechanisms (REA, 2023), including investment subsidies, tax incentives, and grants by the Federal Government of Nigeria. 'Energizing Education' and the technical assistance component of the NEP are fully funded by the Federal Government.

Without a doubt, the NEP is yielding positive outcomes in line with the green transition agenda of the Nigerian government through low-carbon energy technologies development and adoptions. The increasing number of firms – 52 Solar off-grid and 61 solar mini-grid companies (REA, 2023, p. 9) are very strong indicators of some of the successes recorded for the NEP initiative. Globally, Nigeria is waxing stronger as an important market destination for solar energy private investors - mini-grid and stand-alone solar home systems (Agbo *et al.*, 2021). Through the NEP Initiative, over 115 solar mini-grids have been constructed, commissioned, and are operational across different locations/regions of Nigeria (Okechukwu Nnodim, 2023), cutting across diverse stakeholders and purposes. More than 3.7 million Nigerian citizens and 681,000 households now have access to solar-powered electricity (REA, 2024). The NEP has also benefited more than 4,600 MSMEs, 3 federal teaching hospitals, 15 Federal Universities, and 400 Primary Health Care centres (REA, 2024). The total installed capacity of solar hybrid mini-grids and solar home systems in Nigeria stands at 15,569 kW and 46,867 kW, respectively (REA, 2024). Consequently, more than 118,000 and 1,454,000 Nigerian citizens now have electricity connections through solar mini-grid and SHS, respectively. Therefore, the NEP initiative remains an important avenue to facilitate and enhance access to low-carbon energy technologies within Nigeria.

Very recently, the Nigerian government launched the Distributed Access Renewable Energy Scale-Up (DARES). The DARES project builds on the strength and achievements of the NEP initiative to further expand sustainable and clean energy access to stakeholders in Nigeria. DARES retains the NEP business model (including financing and incentive mechanisms) and project components; however, with a wider/broader scope of intended stakeholders' reach. For instance, the DARES clean energy initiative aims to benefit more than 260,000 MSMEs and about 17.5 million Nigerians (World Bank, 2023) through the deployment of solar mini-grids and stand-alone solar home systems. The clean electricity access project initiative is funded by a US\$ 750 million World Bank credit facility and also leverages about US\$ 1 billion private sector investment/capital (World Bank, 2023). Furthermore, the DARES energy project is also funded

by notable international partners, including the Global Energy Alliance for People and Planet; the Japan International Cooperation Agency; the German Development Agency (GIZ); the United States Agency for International Development; the African Development Bank; and Sustainable Energy for All (SEforALL). Globally, the DARES initiative is currently the largest ever single energy-distributed co-funded project by the World Bank and other international funding donors/partners (World Bank, 2023).

#### *Hydro Powered Energy Initiatives*

Hydropower systems as part of low-carbon energy technologies have continued to receive increasing investment attention among critical stakeholders (both public and private) in Nigeria. The drive towards the implementation of the National Water Resources Master Plan (2020-2030) to harness the inherent economic potential of Nigeria's vast water resources (though largely untapped) for the well-being of the country's citizens is an important factor stimulating government and business investments in hydropower projects in Nigeria. In addition, hydropower provides one of the cleanest sources of electricity (Olanipekun and Adelakun, 2020), thus, very significant to Nigeria's electricity access and expansion efforts. In Nigeria, public and private investments in hydropower favour large-scale hydropower projects over small-scale ones (Owebor *et al.*, 2021). The hydropower investment bias is premised on the huge potential contribution of large-scale hydropower projects to the national grid. Usually, large hydropower projects are linked to the main national grid to increase the energy supply capacity of the grid; thus, they provide energy access far beyond the community within which the plants are located. Furthermore, the urgent need to meet the energy demand of the growing Nigerian population (the most populous in Africa) might also account for the increasing investments in large-scale hydropower projects in Nigeria. Some of the very recent large-scale hydropower generation projects in Nigeria are shown in Table 2 (below). There are two major investment patterns for the large-scale hydropower project in Nigeria; on the one hand, direct funding from international partners, including the World Bank, African Development Bank (AfDB), and the China Eximbank; and on the other hand, public-private partnership, particularly, concessions and the build-operate-transfer business model. The 360MW Gurara II hydropower project is being funded by the China Eximbank loan facility of about US\$1 billion (Custer *et al.*, 2023). In addition, the design, construction, and implementation of the majority of Nigeria's hydropower projects are predominantly anchored by private business investors through a concession or agreement with the Federal Government of Nigeria.

#### *Wind-powered Energy Initiatives*

The Katsina wind farm (10MW) is the first wind-powered energy source deployed to address the electricity deficit in Nigeria. The Katsina wind farm (10 MW) was funded (Euro 18.5 million) by the Japan International Cooperation Agency (JICA) (ECREE, 2023). Moreover, the only licensed private wind energy, JBS Wind Power Ltd, that is expected to generate 100MW, is yet to be fully operational in Nigeria (Agbaitoro, 2017), thus, a signpost to the abysmally low-carbon wind energy-based investment in Nigeria.

**Table 1: List of Recent Hydropower Projects in Nigeria**

S/N	Hydropower Project	Installed Capacity(MW)	Status	Location
1	Gurara	360	Completed	Kaduna State
2	Kashimbila	40	Completed	Taraba State
3	Dadin-Kowa	40	Completed	Gombe State
4	Gurara II	360	Ongoing	Niger State
5	Kiri	36	Ongoing	Adamawa State
6	Itisi	40	Ongoing	Kaduna
7	Bawarku	182	Ongoing	Benue
8	Markurdi	1,650	Ongoing	Benue
9	Katsina-Ala	460	Ongoing	Benue
10	Farin-Ruwa	20	Ongoing	Nasarawa State
11	Manya	182	Ongoing	Taraba State
12	Tede	220	Ongoing	Oyo State
13	Mangu	182	Ongoing	Plateau State
14	Lokoja	750	Ongoing	Kogi State

**Source:Okechukwu Nnodim (2022, 2024)**

## **5.0 Barriers to Low-carbon Energy Access in Nigeria**

Despite the recent significant efforts by the government and private sector in Nigeria to increase access to low-carbon energy technologies in Nigeria low-carbon energy technologies adoption in Nigeria is significantly slow (Nwachukwu *et al.*, 2024). Therefore, this section discusses some of the factors mitigating low-carbon energy access in Nigeria.

*Economic Issues:* Analysis has shown that small decentralized low-carbon energy technologies are cheaper than grid extension for remote areas. For instance, in evaluating a solar photovoltaic (PV) system with a capacity of 130 W and a wind turbine generating 150 W, studies have shown that the levelized electricity costs associated with PV technology are competitive to grid extension energy costs (Thiam, 2010) while taking into consideration the population density and distance from the grid. Another issue is the 2010 Regulations by the Nigerian Electricity Regulatory Commission (NERC) where applicants for off-grid or mini-grid licenses must pay no



less than USD 10,556 for application and permit fees (Ole, 2020). Making these fees mandatory before acquiring a captive permit or off-grid/mini-grid license exacerbates the current barriers hindering the development of off-grid low-carbon energy technologies. Other economic related challenges that affect implementation of low-carbon energy technologies include the absence of subsidies for low-carbon energy, high upfront investment expenses, oversight concerning future fuel costs associated with fossil fuels, significant transaction costs for small decentralized systems, and a lack of coherent pricing regulations (Carneiro and Gomes, 2019; Amupolo *et al.*, 2022).

*Policy and Regulatory Framework:* In terms of policy and regulatory frameworks, there is often a lack of continuity and coherence in energy policies, with frequent changes and a lack of long-term strategic planning. Bureaucratic red tape and regulatory barriers are also delaying the implementation of low-carbon energy technologies. At the same time, the high upfront costs of low-carbon technologies deter both private and public investments. While there are long-term savings and benefits, the initial financial outlay is often prohibitive. Many investors and small-scale energy producers struggle to secure financing due to perceived risks and a lack of financial products tailored to the renewable energy sector.

*Cost of grid extension:* Presently, Nigeria's transmission network spans 12,337 km, comprising 5,650 km of 330 kV lines and 6,687 km of 132 kV lines. Implementation of off-grid low-carbon energy technologies is usually attractive for rural settings. However, the residents generally have minimal electricity needs and tend to reside in closely knit communities scattered across vast geographical areas. Bringing the grid to these regions will require a significant upfront investment (Cyril *et al.*, 2024). In the rural areas of Nigeria, it was estimated that the typical cost per household for grid technology stands at US\$899, whereas for mini-grids, it's US\$775. In terms of recurring costs annually, grid technology households incur US\$318, while mini-grid households spend US\$316.

*Research and Development (R&D) Capacity:* Nigeria has made significant strides in building local content and R&D capacity in low-carbon energy technologies, especially via the establishment of various Energy Commissions, notably, low-carbon Energy Research Agencies; however, the research and innovation centres are very weak in bringing about the much-expected carbon-neutrality agenda of the Country (Ogbonna *et al.*, 2023). The uptake of research output emanating from the research institutions by private enterprises, especially the low-carbon energy technologies manufacturers, is abysmally low. The growing importation of low-carbon energy technologies is indicative of the weak linkages. Consequently, local manufacturers of low-carbon technologies (solar PV as a case) in Nigeria are quite negligible. There is a wide disconnection among relevant stakeholders, chiefly, the low-carbon energy research agencies, universities, and private investors in low-carbon energy in Nigeria. The needed national innovation synergy that could integrate local content and R&D capacity in the development of the low-carbon energy sector for the Nigerian economy is typically low and weak. The weak R&D capacity in low-carbon energy technologies may be a reflection of the very weak interaction among the key elements of the national innovation system in Nigeria.

*Tariff Structure:* Affordability constraints in rural communities result in the provision of low tariffs. Nevertheless, this approach tends to yield negative returns as the collection of such tariffs offers little incentive for investment in low-carbon energy systems, most especially in the rural electrification projects (Castro *et al.*, 2022; Cyril *et al.*, 2024). At the same time, the absence of secure regulatory tenure and the possibility of subsidized tariffs for electricity sourced from the main grid also pose a significant risk of stranded investments upon the arrival of the main grid,

thereby jeopardizing private sector involvement and investment in off-grid energy supply (Mambwe *et al.*, 2022). However, the Rural Electrification Agency (REA) in Nigeria offers capital cost subsidies that have been instrumental in advancing mini-grid development by facilitating access to finance and reducing tariffs. Certain mini-grids adopt a hybrid ownership structure where federal funding is provided by the government while local communities contribute land and ensure site security (Zebra *et al.*, 2021).

*Socio-economic Peculiarities:* In Nigeria, low-carbon energy electrification expansion predominantly focuses on unserved and underserved customers (households and MSMEs). The critical mass of the low-carbon energy technologies targets rural dwellers and/or stakeholders with very low purchasing power. The prevailing inflation (31.7%) has exacerbated the poverty rate in Nigeria (National Bureau of Statistics, 2023; World Bank, 2024), pushing millions of people into poverty. Existing low-carbon energy infrastructure is not cost-friendly and optimal (Amo-Aidoo *et al.*, 2022), particularly in the African country context. Therefore, a large proportion of Nigerian citizens are incapacitated to bear the cost burden effects of the high initial/upfront cost of low-carbon energy investment in Nigeria. Thus, a significant barrier to low-carbon energy technologies accessibility and adoption, particularly evident in Nigeria.

*Technical Issues:* Many developing countries are faced with different technical challenges in implementing low-carbon energy systems. For instance, analysis of key stakeholders in the renewable energy sector in Nigeria revealed that insufficient technology and infrastructure pose significant obstacles to the sector (Abdullahi *et al.*, 2022; Cyril *et al.*, 2024). This issue is further compounded by a deficiency in local expertise for installing and maintaining solar PV systems. Another study using the Social, Technical, Economic, Environmental, and Political (STEEP) model to examine the challenges facing micro-grids in remote Nigerian communities reported that subpar materials and a scarcity of skilled local practitioners as major industry impediments (Cyril *et al.*, 2024). Furthermore, the necessity for robust monitoring systems and inadequate project supervision are also critical technical challenges. To fully address these gaps, Nigeria needs a robust policy and regulatory framework that supports the adoption and integration of low-carbon energy technologies. This includes providing incentives for low-carbon energy investments, developing clear and consistent policies that encourage the private sector, and enhancing the capacity of governmental institutions to implement and oversee these initiatives effectively. Adequate implementation of existing policies, such as the Sustainable Energy for All Action Agenda (SE4ALL-AA) and addressing identified challenges to the low-carbon energy technology adoption and diffusion, renewable energy resources can become a significant component of the energy mix in Nigeria.

More specifically, incentives should be introduced to stimulate increased private investment in low-carbon energy technologies within the country. Implementing a subsidy scheme to reduce the costs of low-carbon energy technologies installations for homeowners would motivate individual households and organizations to adopt these systems as backup solutions instead of relying on petroleum generators, which are currently prevalent. Rural residents could benefit from such subsidies to install their power systems, significantly addressing the rural electrification challenge. It has been demonstrated that low-carbon energy technology subsidy schemes do not need to be permanent, particularly if local production of low-carbon energy technologies is underway in the country. In the meantime, the Central Bank of Nigeria should provide assurances to financial institutions regarding the security of lending for low-carbon energy projects. This reassurance will encourage private investment and the individual purchase of low-carbon energy technologies by making affordable credit facilities more readily available. At the same time, there should be immersive training programs and partnerships with educational institutions to build a

skilled workforce capable of supporting the low-carbon energy sector. Additionally, international cooperation and financial support will be crucial in addressing the high initial costs associated with renewable energy projects.

Investing in technological innovation and infrastructure development is essential. The government should evolve and promote innovative financing models such as green bonds, public-private partnerships, and microfinancing to lower the entry barriers for low-carbon projects. In addition, subsidies, grants, feed-in tariffs, and other financial incentives to reduce the initial cost burden on investors and consumers should be implemented. Research and development in low-carbon energy technologies should be prioritized to adapt these technologies to local conditions and enhance their efficiency and affordability. Infrastructure improvements, such as modernizing the grid to handle low-carbon energy inputs and developing energy storage solutions, are also critical for ensuring the reliability and effectiveness of low-carbon energy systems.

## **6.0 Conclusion**

This study investigates the key factors influencing the adoption of low-carbon energy technologies in Nigeria. Through a comprehensive analysis of existing literature, it identifies critical enablers that could accelerate the shift toward sustainable energy solutions. The insights generated hold significant value for energy sector practitioners, researchers, government agencies, and environmental advocates involved in renewable energy development and deployment. The adoption of clean energy sources – including solar, wind, hydro, and biomass - presents a multi-faceted solution to Nigeria's pressing energy challenges. These technologies can simultaneously improve electricity reliability, decrease greenhouse gas emissions, and enhance public health by reducing pollution-related illnesses. Beyond environmental benefits, access to renewable energy represents a vital tool for promoting social justice, strengthening energy independence, and driving economic progress.

With exceptional solar and wind resources, Nigeria occupies a strategic position to dramatically reduce its carbon emissions. Transitioning to clean energy would enable the country to honour its commitments under the Paris Agreement while building climate resilience against growing threats like desertification and coastal flooding. The economic rationale is equally compelling as low-carbon energy technologies offer price stability compared to volatile fossil fuel markets, and create employment opportunities across the value chain, from production and installation to operations and innovation. This study acknowledges several research constraints that point to valuable future directions. While focused on Nigeria's unique context, comparative analyses with other nations could yield additional insights. Though grounded in rigorous literature review, subsequent studies might incorporate perspectives from diverse stakeholders through empirical research. Furthermore, emerging technologies like artificial intelligence present promising avenues for optimizing sustainable energy systems. Ultimately, Nigeria's journey toward a clean energy future presents both obstacles and extraordinary potential. Realizing this vision will require coordinated strategies that harness the nation's natural advantages, skilled workforce, and technological ingenuity. Successful implementation promises not only domestic energy security and economic transformation but also meaningful contributions to global climate action.

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