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Renewable Energy Integration in Nigeria: A Critical Review of Challenges, Progress and Future Prospects

Ogunboyo Partrick Taiwo[1]; Magi Emoemi Stephen[2]; Ailemen Divine Omoefe[3]

[1]Department of Electrical and Electronics Engineering, Federal University of Technology and Environmental Sciences, Iyin Ekiti
[2]Department of Electrical and Electronics Engineering, Olusegun Agagu University of Science and Technology, Okitipupa, Ondo State
[3]Department of Electrical and Electronic Engineering, University of Ibadan, Ibadan, Oyo state

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Abstract

Energy challenges plague Nigeria. Its inability to meet energy demand through conventional and natural resources has led to greater reliance on nonrenewable sources for power generation. While solar, wind, hydropower and biomass possess potential for energy security and development in Nigeria, getting these forms of energy into the grid is a challenge posed by a number of technical, legal, financial and institutional barriers. This paper introduces the subject of challenges to the incorporation of renewable energy into Nigeria's power grid by examining potential of such energy within Nigeria and the nation's legal frameworks. It examines other countries who are major users of renewable power and challenges they face within their own jurisdictions. The findings clearly show that even with the magnitude of potentials renewable energy possesses, numerous challenges pose great barriers to getting it through the power grid. Problems emanate from policies, lacklustre infrastructure, insufficient funds and various social and economic barriers. The paper draws conclusions and proffers suggestions on how to overcome these. In summary Nigeria with all the resources that nature has to offer can play a major role in renewable energy but this will not be achieved with the current systemic weaknesses embedded in her establishments. A multi-dimensional strategy is therefore necessary comprising the use of technology to create a smart grid, updates and reforms to law and policy regarding the inclusion of renewable energy in power generation, and building of in-house expertise to service the renewable energy sub-sector. Financial instruments must be structured to grant cheap, long-term loans for these very projects.

Keywords: *Renewable Energy Integration, Nigeria, Grid Infrastructure, Energy Transition, Solar Energy, Wind Energy, Policy Framework, Sustainable Development.*

I. INTRODUCTION

The world is evolving in terms of energy development due mainly to the effects of climate change, energy security issues and the Sustainable Development Goals agenda [1, 2]. Renewable Energy Sources technologies generally are evolving rapidly and solar photovoltaic and wind have gained prominence. However, established renewable energy sources like hydropower and biomass power remain critical. This is especially so in sub-Saharan Africa and Nigeria where renewable energy is not a choice but a necessary ingredient for sustainable energy development and real improvement of livelihoods [3, 4]. Nigeria, which is the most populous nation in Africa with over 220 million people, has one of the lowest per capita electricity consumption in the world [5]. As the most prominent oil producer in Africa with reserves ranking top five globally [6], Nigeria is reportedly experiencing perennial electricity supply deficit [7]. The national grid has installed power generation capacity of about 13,000 MW; however, the energy available on the grid has been constantly ranging between 4,000 MW and 5,000 MW far below the peak demand which stands at over 30,000 MW [8, 9]. These issues, coupled with the deteriorating condition of the aging power transmission and distribution infrastructure, constitute a major developmental challenge in Nigeria [10, 11].

For an all-encompassing energy solution, the integration of renewable energy into the grid becomes necessary. Nigeria has one of the world's most prolific sunlight resources, with average daily solar radiation on horizontal surface ranging from 3.5 kWh/m² in the south-western part of the country to about 7.0 kWh/m² in the north [12]. In addition to solar energy, the country has wind energy potential large enough to establish tens of megawatts of wind farms around the country, particularly on the Jos Plateau and other parts of northern Nigeria [13]. Moreover, apart from the existing large hydro electricity installations at Kainji, Jebba and Shiroro, there are also vast resources of run-of-river hydropower along the Niger and Benue rivers [14, 15]. Additionally, the country has immense biomass energy resources inherent in agricultural residues and municipal solid waste [16].

Africa is bestowed with enormous solar, wind and geothermal resources that could fuel a sustainable renewable energy industry; but conversion of this endowment into workable renewable energy programmes that could be optimally channeled into the grid is not an easy task [17, 18]. Most renewable energy options are beset with unique sets of technical, legislative, funding and societal challenges including power grid stability, Reverse Power Flow, low voltage, voltage regulation difficulties and the paucity of robust smart infrastructure [19, 20, 21]. Notably, even with a plethora of policies such as the National Renewable Energy and Energy Efficiency Policy of 2014 and the Renewable Energy Master Plan of 2019 developed by the Energy Commission of Nigeria [22, 23], implementation and integration of these policy instruments in a holistic manner are still a challenge. However, with the increased need to meet up energy demands, this paper provides updated information on renewable energy integration into Nigeria's power mix.

The paper examines the renewable energy resources in Nigeria as well as policy and regulatory framework related to renewable energy in the country. It identifies technical challenges as well as non-technical challenges that hinder successful integration of renewable energy into Nigeria's grid. Some ongoing and completed projects in Nigeria related to renewable energy integration are discussed. Also, experiences of best practice globally related to renewable energy integration are examined to identify challenges and propose a road map for future reference. The paper is organised into eight sections. Section 2 covers Renewable Energy Resources in Nigeria. Section 3 discusses Renewable Energy Policy and Regulations in Nigeria. Section 4 reviews Renewable Energy Grid Integration Challenges. Section 5 examines Challenges related to Financing Renewable Energy. Section 6 presents Case Studies of successful Renewable Energy Projects. Section 7 covers Global Experience on Renewable Energy Integration. Section 8 presents the Implementation Road Map for Renewable Energy Integration in Nigeria.

II. RENEWABLE ENERGY RESOURCE POTENTIAL IN NIGERIA

➢ *Solar Energy*

Nigeria has some of the best solar resources in the world. The average daily solar radiation in the country is about 5.5 kWh/m², with the southern coastal areas getting about 3.5 kWh/m² and the semi-arid north-eastern areas getting almost 7.0 kWh/m² [12, 13]. This means that the country could produce about 427,000 TWh of solar energy per year, which is many times more than the country can currently generate [22, 24]. Nigeria is one of the best places in the world to install solar PV because of this resource, and solar energy is probably the most important way to quickly increase renewable capacity [2].

However, there have not been many practical applications for this potential. As of 2022, Nigeria's installed solar PV capacity was still less than 100 MW. Most of it was made up of small off-grid and mini-grid systems, and there were not many large utility-scale projects [5, 25]. The Energising Education Programme and the Rural Electrification Agency mini-grid projects are important recent steps forward, but they do not come close to unlocking the country's solar potential at grid scale [26, 27].

➢ *Wind Energy*

Wind energy resources in Nigeria exhibit huge potential from local to regional scale based on their geographical distribution. The northern highlands including the Jos Plateau, Sokoto, Kano and Maiduguri experience wind speed of 4 to 7 m/s at 10 m above ground level but at standard hub height of 50 to 80 m the wind speed is high enough to extract technically exploitable energy that can be used to establish wind farms [28, 13]. The Energy Commission of Nigeria has predicted wind energy potential of over 40,000 MW from some favourable locations in the country [29].

Wind energy has enormous untapped potential in Nigeria and although some studies have been carried out, there are no major utility-scale wind farms commissioned so far. Major challenges hindering the growth and development of wind energy in Nigeria include the huge capital cost of wind turbine generators and their installation, lack of local fabrication capacity for wind turbines, over-stretched weak transmission infrastructure in windy remote locations and lack of reliable long-term wind climate data which are essential for informed decision making [28, 17, 30].

➢ *Hydropower*

Nigeria currently operates the largest installed renewable energy capacity in the country in the form of hydropower with the three major facilities at Kainji, Jebba and Shiroro having nameplate capacities of 760 MW, 578 MW and 600 MW respectively. However, due to low reservoir levels, ageing turbines and poor maintenance, an average of about 350 MW is actually generated [7, 24]. In addition to the major facilities, more than 278 small hydropower sites with potentials greater than 3000 MW have been identified [14, 22].

Small and mini hydropower plants have lately gained the focus of policy makers in their drive to provide rural electricity supply under the Rural Electrification Strategy [31, 32]. However, the impact of seasonal variability of hydro resources, environmental assessment issues and funding challenges to execute installation at distant locations have impeded achievements [27, 33].

- *Biomass Energy*

Agricultural and forestry residues such as rice husk, sugarcane bagasse, cassava peels and wood waste are abundant in Nigeria [16, 34]. These residues can serve as significant biomass energy sources. Available statistics show that technically recoverable biomass energy resource in Nigeria is estimated at over 144 Mtoe annually [22]. Biomass further includes municipal solid waste pervading urban centres across Nigeria which can also serve as feedstock for biogas and waste-to-energy programmes [24]. Apart from industrial uses, biomass and biogas are increasingly providing energy needs of rural dwellers who combust them in traditional forms such as wood and charcoal leading to indoor air pollution and deforestation [35, 36].

Despite the huge potential of biomass resources for energy, modern biomass energy conversion technologies such as gasification, anaerobic digestion and combustion for electricity generation are still in their infant stages in Nigeria. Currently there are only a few bagasse cogeneration schemes in place in the sugar mills. Grid-connected biomass power plants are still scarce in Nigeria [29]. A number of barriers affect the growth of the emerging biomass-to-power sector in Nigeria including the lack of certainty of supply through the biomass supply chain, the technology transfer and implementation gap and lack of specific biomass feed-in tariff incentives and regulations [37, 23].

III. POLICY AND REGULATORY FRAMEWORK FOR RENEWABLE ENERGY INTEGRATION

- *Overview of National Policy Instruments*

Since the early 2000s, Nigeria's formal policy framework for renewable energy has changed a lot. The Nigerian Electricity Power Policy of 2001 started the process of making the power sector more open. This opened the door for independent power producers and set the stage for renewable energy participation [10, 38]. The Electric Power Sector Reform Act of 2005 set up the rules and regulations that govern the current structure of the sector. This included the creation of the Nigerian Electricity Regulatory Commission and the splitting up of the state-owned Power Holding Company of Nigeria into successor Generation Companies and Distribution Companies[39, 40].

The Energy Commission of Nigeria made the Renewable Energy Master Plan in 2005 and updated it in 2012. It set high goals for increasing the amount of renewable energy in the country's energy mix, such as having 23,000 MW of renewable capacity by 2025 [22, 29]. The National Renewable Energy and Energy Efficiency Policy of 2014 has further strengthened these goals by laying out a detailed plan for improving energy efficiency and the development of solar, wind, hydro and biomass resources [22, 41]. Nigeria's Intended Nationally Determined Contribution under the Paris Agreement, submitted in 2015, committed the country to reduce greenhouse gas emissions by 20% unconditionally and up to 45% conditionally by 2030 with significant roles envisaged for renewable energy expansion and fossil fuel subsidy reduction [42, 43]. These developments have made renewable energy policy more important in politics but it has still been hard to turn big goals into real programs [17, 44].

- *Regulatory Mechanisms: Feed-in Tariffs and Net Metering*

The Multi-Year Tariff Order framework was created by Nigerian Electricity Regulatory Commission to make it easier for people to invest in renewable energy. It includes rules for feed-in tariffs for eligible renewable generators [9, 45]. Nigerian Electricity Regulatory Commission also made the Mini-Grid Regulations of 2016 and the Meter Asset Provider Regulations. These rules are meant to make it easier for people in off-grid communities to get electricity and to encourage private investment [9]. There have been suggestions for net metering frameworks that would let small-scale renewable generators send extra electricity to the grid and get credits, but these ideas are not always put into practice by Distribution Companies [46, 47].

Analysts have widely condemned the Nigerian feed-in tariffs regime for providing rates that fail to entice commercial investment, especially in light of the significant perceived political and macroeconomic risks [48, 49]. The lack of a strong renewable energy certificate market, limited access to competitive financing and currency volatility make feed-in tariffs driven investment even less appealing [30, 17]. The World Bank helped start the Power Sector Recovery Programme in 2017. It was meant to help the whole sector with its financial problems, but it has not had much of an effect on integrating renewables [48].

- *Critical Assessment of Policy Implementation Gaps*

Nigeria is said to be committed to increasing use of renewable energy to meet her energy needs. Realizing this dream, however seems challenging due to some institutional bottlenecks [17, 50, 18]. Even though the existing policies and regulations are adequate, what is critical is the structural impediments in the pursuit of increasing utilisation of renewable energy for sustainable energy delivery. The institutions which have roles to play in boosting renewable energy comprise the distribution companies, the regulatory bodies like Nigerian Electricity Regulatory Commission and Energy Commission of Nigeria and the other ministries, agencies and departments responsible for the promotion and implementation of renewable energy programmes like the Federal Ministry of Power and the Rural Electrification Agency. However, conflicts, overlapping functions and double applications of similar resources have been observed in these institutions at different times [51, 52].

Among the Distribution Companies for instance, financial strength is a great challenge. The industry is presently regulated by a tariff regime which is below the cost recovery levels and therefore lacks the financial capacity to inject funds into the operational networks for upgrade and integration of Renewable Energy Sources [9, 53]. Furthermore, the challenges of both implicit and explicit subsidy on fossil fuel outweigh those of renewable energy sources [54, 6].

IV. TECHNICAL CHALLENGES OF GRID INTEGRATION

- *Grid Infrastructure and Network Stability*

The integration of renewable energy into the nation's power generation mix is being hampered by the deplorable state of the existing power transmission and distribution infrastructure. The aged power transmission infrastructure is suffering from serious operational losses within the range of 18 to 25% while the current reactive power compensation for real power transmission is grossly inadequate and causes power angle distortion thereby making the network prone to failure with a fragile configuration which can collapse at any time resulting in power shortfall and poor stability of the electrical power system [55, 11, 56]. The current Transmission Company of Nigeria has a vast 16,000 circuit kilometres of 330 kV and 132 kV overhead lines and a woefully inadequate wheeling capacity to transmit huge quantum of renewable energy from remote generation sites to their load centres [7, 40].

The grid is subjected to additional stress as more variable renewable energy sources including solar and wind penetrate into the grid [57, 58]. Therefore, there is a need to invest in grid flexibility provisions like fast-response backup generation, demand response and energy storage [59, 60]. Currently the Nigerian grid lacks ancillary service markets and mechanisms for grid balancing. Therefore, the grid may experience severe problems including frequency deviations and voltage instability when the renewable penetration exceeds a certain threshold [61, 62].

- *Reverse Power Flow and Protection Coordination*

Grid integration of Distributed Renewable Energy sources into the radially configured power distribution network is fraught with numerous technical challenges including the problem of Reverse Power Flow. Reverse Power Flow occurs when the power generated by distributed renewable generation sources within a substation exceeds the loads within that substation thereby causing power to flow back in the opposite direction of the originally intended flow path, as opposed to the design intent of a uni-directional power flow in a typical power network configuration [63, 64]. These occurrences are more pronounced with wind energy sources, as noted by Ogunboyo and Ogunlade [65], Ameur et al. [66], and they pose serious threats to both operational quality and safety of the power networks including the risk of overvoltage at the Point of Common Coupling, overload of conventional protection relays and escalation of fault current magnitude.

Due to high loading on distribution transformers and protection apparatus, Reverse Power Flow may pose great challenge to power system reliability by even accelerating the aging of power system equipment [67, 68]. As distribution systems are expected to operate on or even beyond design basis, the impact of Reverse Power Flow on current and voltage magnitudes and phase angle will be more critical. Reverse Power Flow affects the coordination of protection devices in distribution systems and requires an adaptive protection scheme [63]. The scheme needs directional overcurrent relays and an energy management system capable of real-time measurements under various Reverse Power Flow conditions. However, such modern schemes require huge investment and operational cost which Nigerian power utilities may not afford at the present stage [46, 31].

- *Power Quality Issues*

Integration of renewable energy sources, especially inverter-based generation systems, introduces a number of power quality issues, for example voltage flicker, Total Harmonic Distortion, unbalanced voltage and others [69, 70]. Majority of grid-connected Photovoltaic inverters and wind turbine converters inject harmonic currents into the power network, wherein harmonics sometimes exceed standard limits defined by regulatory bodies like IEC 61000-3-6 and IEEE 519 [71]. In the Nigerian scenario, which has a highly weakly meshed distribution network, these power quality disturbances easily propagate to affected points and pose serious threat to the operation of sensitive loads like industrial machinery and large commercial establishments [72, 73].

Active power filters, Static Volt-Ampere Reactive Compensators and Dynamic Voltage Restorers have been researched as potential solutions to counteract power quality disturbances. Although these systems have been proposed and researched [74, 75], their implementation in Nigeria faces great challenges such as the high cost of installation and repair and the lack of skilled engineers to do the job [76, 40]. Moreover, the lack of a power quality monitoring infrastructure and the absence of a grid code which demands power quality compliance by renewable generators connected to the grid pose great challenges. Therefore, installing a power quality monitoring infrastructure and a stringent grid code to be complied with by renewable generators connected to the grid are necessary guidelines for the near future.

- *Smart Grid Requirements*

Achieving high penetration levels of variable renewable energy without compromising grid reliability requires the deployment of smart grid technologies, Advanced Metering Infrastructure, Wide Area Monitoring Systems, automated voltage regulation and intelligent load management platforms [77, 59]. In developed economies, smart grid investments have enabled grid operators to manage renewable variability through demand-side response, distributed storage and real-time grid optimisation [78]. For Nigeria, the absence of smart metering with an estimated Advanced Metering Infrastructure penetration below 5% and the limited digitalisation of the distribution network represent critical gaps that will need to be addressed before high renewable penetration is safely achievable [47, 79].

- *Financial and Economic Barriers to Renewable Energy Integration*

- *Investment Climate and Risk Perceptions*

In Nigeria, the financing of renewable energy projects is constrained by an unfavourable investment environment. High levels of political risk, currency uncertainty, tariff and policy volatility, as well as difficulties in enforcing contracts impede the financial development and operational sustainability of the renewable energy market [48, 80]. Currently, international investors and financiers are unwilling to invest in Nigeria due to high risk-adjusted returns expected from developers. The expected return on equity for developers in Nigeria reportedly ranges between 20 to 30%. This is considerably higher than the expected return on equity in mature renewable energy markets, reportedly averaging 8 to 12% [32, 49].

Despite recognition of its investment potential, the Nigerian electricity market remains challenging to investors. The tariffs set by the market operator for electricity supply are below the levels required for cost recovery. Additionally, the level of Aggregate Technical, Commercial and Collection losses in the distribution network is high, while the level of debt in the value chain is an embarrassment. The support of international financial institutions such as the World Bank and African Development Bank through guarantee instruments or partial risk coverage has been felt but this has been insufficient to de-risk renewable energy investments to the level required to tackle the investment gap in the power sector [9, 53]. De-risking financing available in the power sector is only partial and insufficient for the challenge at hand [81, 4].

- *Access to Concessional Finance and Green Financing Instruments*

Complementing private investment to address Nigeria's renewable energy financing gap, there is also a need for access to concessional financing including green bonds, climate finance from multilateral development banks and bilateral aid [30, 5]. Although Nigeria has started to access some of these resources, the volume is far below needs. For instance, the country's first sovereign green bond was issued in 2017 to raise NGN 10.69 billion to support renewable energy and climate change related projects [2]. But there is a need for Nigerian institutions to build capacity to prepare bankable project proposals and meet environmental and social safeguard standards required internationally [80, 48].

- *The Cost Competitiveness of Renewable Energy*

Recent improvements to the long-term financial outlook of renewable energy sources in Nigeria include a dramatic decline in the global costs of solar and wind energy. Solar Photovoltaic has become the cheapest new source of electricity in most of the world, with the global weighted average levelised cost of electricity for utility-scale solar Photovoltaic decreasing by 89% since 2010 [25]. Similarly, onshore wind electricity costs have decreased by 70% over the same period [25, 82]. Although solar and wind costs have decreased in cost relative to gas-based generation in Nigeria, costs must also be placed on the frequent power outages suffered by Nigeria and the expenditure involved in running generators, including diesel-powered ones [36, 83].

However, studies by Dioha and Kumar [26] and Bukar et al. [84] revealed that the lifetime costs of solar-battery or solar-diesel hybrid systems can be lower than or equal to the present grid electricity tariffs in many parts of Nigeria, thereby paving the way for speedy integration of RES. But this can only become a reality if appropriate financing options and required support infrastructure are put in place [17, 23].

V. REVIEW OF SELECTED RENEWABLE ENERGY PROJECTS IN NIGERIA

- *Rural Electrification Agency Mini-Grid Programme*

The Rural Electrification Agency in Nigeria is making a significant impact in renewable energy development. The agency has installed over 200 solar mini-grid sites across different states [81, 26]. The mini-grids operate in a capacity range between 10 kW to 500 kW. The systems are made up of solar panels, battery storage and local distribution networks. These projects have assisted in the way electricity is accessed and also enhanced the living conditions in communities like the rural areas [27, 32]. Nigeria needs not only an increase in investment but also expertise in the technical field to help provide access to electricity to about 90 million people currently without power [5, 4].

With these improvements, lots of challenges still exist in implementation such as land ownership issues affecting both project siting and long-term planning. Community acceptance influences both project success and sustainability. Poor maintenance reduces system performance, not only due to weak system structures but also due to a lack of skilled technicians [80, 85]. Addressing these challenges will not only improve system performance but also position solar energy as a sustainable solution to Nigeria's energy needs. With strong commitment and clear policy direction, Nigeria can achieve improved rural electrification and a better quality of life.

- *Energising Education Programme*

The Energising Education Programme is implemented by the Rural Electrification Agency with funding from the Nigerian government. The programme aims to supply reliable electricity to both 37 federal universities and 10 teaching hospitals using solar hybrid systems [38, 23]. The programme addresses poor power supply in higher institutions and many of these institutions depend on costly and polluting diesel generators. The initiative will not only improve electricity supply but also reduce energy cost and environmental impact in Nigerian institutions. By 2022, several installations were completed in institutions like the University of Lagos, Usmanu Danfodiyo University and the Federal University of Technology, Akure [23, 2].

The Energising Education Programme shows that solar power can work effectively on a large scale in Nigeria. The programme proves that solar hybrid systems can perform well under local conditions. The project provides useful data on system performance, maintenance needs and user satisfaction [86, 87]. The programme mainly focuses on institutions and does not significantly increase national grid renewable capacity. The programme builds local technical skills in solar technology and also increases investor confidence in solar energy projects [50, 88].

➢ *The 2,000 MW Solar Power Programme*

Nigeria plans to connect 2,000 megawatts of solar power to the national grid. The government introduced the Presidential Renewable Energy Initiative to achieve this target. The government also launched a competitive bidding programme for international companies to develop solar power plants [22, 38]. Many companies submitted bids for the projects. The project implementation has been slow due to delays in financial closure. Financing challenges affect project development. Poor creditworthiness of power off-takers discourages investors. Limited government guarantees reduce lender confidence [48, 49].

Nigeria's renewable energy programmes often follow a similar pattern. The government sets ambitious targets and designs good procurement frameworks as implementation challenges usually arise during execution. The weaknesses of the structure in the power sector always cause these setbacks [17, 50]. Some of the projects executed in the past like the 2,000 MW programme provide important lessons. Strong risk-sharing guarantees improve investor confidence and standardised power purchase agreements will ensure consistency. Better financial support for distribution companies strengthens the market. These measures will improve the success of future renewable energy projects in Nigeria.

➢ *Global Best Practices and Their Applicability to Nigeria*

- *South Africa's Renewable Energy Independent Power Producer Procurement Programme*

In 2011, South Africa launched the Renewable Energy Independent Power Producer Procurement Programme. The programme stands as one of the most successful renewable energy models in Africa and other developing regions [48, 82]. The programme uses a competitive bidding process and companies compete to supply renewable energy. It applies standardised contracts that financial institutions can easily understand. Government provides payment guarantees for energy supplied and reduces investor risk. The programme also sets clear eligibility rules for participating companies. These features have attracted over 14 billion dollars in private investment. The programme has delivered over 6,400 megawatts of wind and solar capacity [2].

For Nigeria, the Renewable Energy Independent Power Producer Procurement Programme shows clear lessons. Standardised contracts improve transparency and also reduce risk. Government-backed guarantees increase investor confidence. Independent oversight ensures accountability in the procurement process [48, 32]. These elements support successful project delivery. Countries that adopt similar approaches can improve renewable energy development. South Africa's model shows that proper structure and policy design can drive large-scale investment in renewable energy. Nigeria can learn from this model and build a stronger and more reliable sustainable energy sector.

- *India's Solar Mission*

India launched its solar mission in 2010 to expand solar energy on a large scale. The mission targeted 100 gigawatts of solar power by 2022 [89, 2]. India reduced the cost of solar energy through competitive bidding among companies. The country achieved one of the lowest solar tariffs in the world at about USD 0.024 per kilowatt-hour [25]. India developed local solar panel manufacturing industries. The country trained a large workforce in solar technology.

India's solar model provides useful lessons for countries like Nigeria. The model supports local industry development and job creation [90, 1]. The model reduces dependence on fossil fuels. The model promotes cleaner and sustainable energy sources. The model helps to reduce environmental pollution. The model also supports efforts to address climate change. India's experience shows that developing countries can achieve large-scale renewable energy success.

- *Smart Grid Technologies in the Nordic Countries*

The countries in northern Europe like Denmark, Finland and Sweden have done a great job of using renewable energy especially wind power. In reality, Denmark often produces more wind energy than it needs. They have achieved this by investing in smart grid technology, connecting their power systems with neighbouring countries and being flexible with energy demand [91, 92]. Even though these countries are very different from Nigeria in terms of society and infrastructure, the basic technical ideas can still be applied. These ideas include being able to closely monitor the grid, making accurate forecasts, using automated systems and being flexible with energy demand [77, 93]. For Nigeria, it is essential to prioritise smart grid investments if they want to successfully integrate a lot of renewable energy into their power system. This is a key lesson that can be learnt from the experience of the Nordic countries [79, 94].

- *Off-Grid Electrification: Bangladesh and Kenya Models*

In areas of off-grid and rural electrification, the experiences of Bangladesh with its highly successful Solar Home System programme, which delivers solar panels to over 4 million households, and Kenya with its rapidly growing mobile-enabled pay-as-you-go solar market offer particularly relevant lessons for Nigeria [95, 96]. The common success factors across these models include innovative financing (particularly micro-credit and pay-as-you-go payment systems), strong local distribution networks, rigorous product quality standards and well-designed government subsidy programmes that are targeted at the poorest households [85, 97]. The Nigeria off-grid electrification strategy which is under the Rural Electrification Agency has drawn on these models but the scale and speed of rollout have remained insufficient relative to the size of the unelectrified population [5, 4].

VI. STRATEGIC RECOMMENDATIONS AND CONCLUSIONS

➢ *Strengthening the Policy and Regulatory Framework*

In Nigeria, renewable energy strategy needs a unified and consistent policy environment. The current system must attract investors and support long-term development. Government should implement a competitive procurement system for large-scale renewable energy projects. The system should follow a model similar to South Africa's Renewable Energy Independent Power Producer Procurement Programme. The system should include standardised Power Purchase Agreements and independent project evaluation processes.

➢ *Grid Infrastructure Investment and Smart Grid Deployment*

Nigeria needs strong investment to adopt the improvement of renewable energy. The country must upgrade the grid infrastructure to support this transition. Government should work on expanding the transmission network to reduce energy losses and increase the capacity. The system must be built in a way that it would be able to handle more electricity from renewable sources. Distribution infrastructure needs serious upgrade too and this includes transformers, protection systems and cable networks. The upgraded system should support Reverse Power Flow from Distributed Energy Resources.

Nigeria should deploy and implement advanced metering infrastructure as well as smart grid technologies across the country. These technologies will enable real-time monitoring, automated control and demand response [46, 47]. Grid operators will manage electricity more efficiently with these systems in place. Adaptive protection systems should also be adopted and directional overcurrent relays and microprocessor-based schemes are good examples. These systems will help improve safety and reliability in high renewable penetration [63, 98].

➢ *Financing and Investment Mobilisation*

Nigeria needs to combine efforts to solve the funding challenges in achieving renewable energy. Various financial strategies should be applied by the country at the same time. Government should use tools like risk reduction such as guarantees and insurance to help attract private investors [81, 32]. Green bond programmes should also be introduced to help fund key renewable energy projects similar to the 2017 initiative [2].

Nigeria should also work on its electricity pricing which should be seen as a serious reform. The system should show the actual cost of power supply. The support for low-income consumers must also be included to ensure affordability [9, 53]. These will improve the financial strength of the distribution companies and will also bring more investment into the sector. Local banks should be encouraged to finance renewable energy projects. This will reduce the foreign exchange risks that developers face [30, 48].

➢ *Local Capacity Building and Research*

Nigeria needs to work on investing in human capacity and local research for renewable energy growth. All higher institutions and colleges across the country should strengthen their teaching in renewable energy engineering, power systems and energy policy. Institutions must also update their curricula to reflect current industry needs [99, 83]. Nigerian institutions should work with international universities on areas like grid integration, energy storage and smart grid optimisation [26, 100].

➢ *Conclusions*

Nigeria is now at a stage where the choices it makes about energy will shape its future. The country holds lots of natural resources and has a large population. The drive for Nigeria to lead renewable energy development in Africa is also growing fast. But it is still seriously fighting technical, regulatory, financial and institutional issues. These challenges have slowed the shift from renewable energy potential to real development. This study has shown that the problems are real and complex which are tied to structural issues that move beyond the energy sector alone.

A proper and well-structured plan should have been created earlier but it has not been done yet. Grid improvement, better policies, adequate funding and strong human capacity must all be part of this plan. Political will from government is not an option because this is the engine that drives everything else. Reliable technical data must be at the centre of every decision. Other countries have shed more light on how it should be done. South Africa expanded their renewable energy base through open procurement. India utilised solar power fast with direct subsidies and land policy reforms. Kenya built its geothermal sector through government reform. The Nordic countries achieved high renewable energy shares through grid flexibility and market design. Bangladesh grew their Solar Home System programme through strong rural policy support. Nigeria can adopt these methods too.

Every stakeholder in Nigeria has a role to play. Policymakers must make targets that are clear as they back them up with law. Regulators must enforce standards without compromise as power companies invest in grid readiness. Investors need clear rules and should be able to take calculated and reduced risk. Researchers must generate local data that drives sound decisions. This paper offers a clear starting point for those decisions to be made and gives the energy future of Nigeria a direction that is practically achievable.

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