

*Original Paper*

## Operational Performance Analysis of Renewable Energy Integration in Nigeria's Power Sector

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### **Abstract**

*Given the increasing demand for electricity and the underperformance of the Nigerian power sector, this study examines the apparent situation of renewable energy integration in Nigeria's power sector by analyzing the renewable energy generated over time, and the operational performance of the generated energy within the power system. Using both longitudinal and ex post facto research designs, secondary data obtained from both the Nigerian Electricity Regulatory Commission and the International Renewable Energy Agency database were analyzed. Descriptive statistics were used to evaluate the data, while time-series forecasting based on an exponential smoothing method was applied to forecast future trends, and an independent sample t-test was applied to compare the performance metrics between renewable energy and gas generation in the power system. The findings indicate that Nigeria's renewable energy, particularly hydro energy, remains dominant, but its electricity distribution is*

*significantly below the installed capacity owing to infrastructure limitations and transmission constraints. In addition, off-grid solar photovoltaics are rapidly expanding. In general, the study indicates that the underperformance of renewable energy integrated into the power system is mainly operational and not resource-based and that there is a need for policy focus to shift from capacity expansion to system flexibility and grid reinforcement to achieve a reliable and sustainable electricity supply.*

**Keywords**

*Renewable Energy, Operational Performance, Nigeria's Power Sector, Energy Integration.*

**1. Introduction**

In Nigeria, a large segment of the population often faces power outages, and many remain disconnected from the power grid. Despite its endowment of resources, the country's power sector faces challenges such as unbalanced generation capacity, interrupted public electricity supply, and high electricity demand (World Bank, n.d.). Consequently, households and small-scale businesses, particularly in rural areas and urban center peripheries, continue to rely on traditional energy sources and fossil-fuel-powered generators to meet their basic and productive energy needs (Akinbami, 2001; Babanyara & Saleh, 2010; Ohunakin, 2010; Okafor & Joe-Uzuegbu, 2010; Yetano Roche et al., 2024). This dependence incurs significant economic costs and poses environmental and health risks associated with fuel use. Therefore, shifting to renewable energy has become a strategic response to Nigeria's energy shortages, environmental issues, and energy security concerns.

Globally, renewable energy has shown significant performance and has become a key solution for reducing the impacts of climate change, promoting sustainable economic growth, and ensuring long-term energy security (Edenhofer et al., 2014; Mccall, 2024). In many countries, especially in Asia, Europe, North America, and parts of Africa, the adoption of renewable energy technologies, such as wind, hydropower, solar, geothermal, and bioenergy, is increasing, driven by specific policies and regulations (Debnath et al., 2025). These efforts have led to notable results, with the share of renewables growing in the global electricity mix. These initiatives have achieved milestones, with the share of renewables steadily increasing in the global electricity generation mix (Sawin et al., 2010). However, the performance of renewable energy systems depends not only on resource availability and capacity but also on their operational efficiency and ability to reliably feed power into the grid.

Nigeria continues to face significant renewable energy integration challenges. These challenges include transmission infrastructure, policy uncertainty, financing issues, technology, currency risks, security risks, and limited access to low-cost funding. Although efforts to implement Nigeria's National Renewable Energy and Energy Efficiency Policy (NREEEP) have promoted public-private partnerships and donor-funded projects, the success of implementation has varied (Iyabo, 2021; Sanni, 2016). Delays in projects, costs and operational overruns are also indicators of the lack of standardized

and effective structures for managing the performance of renewable energy integrated in the power sector.

The energy mix in Nigeria's electricity sector is diverse, with natural gas accounting for approximately 70% to 79% of electricity generation. This is followed by hydro energy, which generates approximately 15% to 20% of the electricity. Conventional energy sources, such as coal and oil, play no significant role in electricity production (Salman et al., 2018). On the other hand, solar photovoltaic technology is said to have tremendous untapped potential. The solar irradiance in Nigeria is approximately 1600-2200 kWh/m<sup>2</sup>, ranging from 4 kWh/m<sup>2</sup> in some regions to more than 7.0 kWh/m<sup>2</sup> in others, particularly in the north (IRENA, 2023a; Sambo, 2009). However, renewable energy development has not resulted in a commensurate increase in electricity supply. Although renewable energy is encouraged as a tool for diversifying the energy mix, ensuring energy security, and advancing environmental sustainability, capacity development is not commensurate with the electricity supply (Adebanji et al., 2022). In power supply systems where infrastructure lacks adequate transmission and distribution facilities, renewable energy capacities remain underutilized, resulting in a significant gap between electricity supply capacity and actual electricity produced (Babayomi et al., 2022).

The system's structural deficiencies, fragile electrical grid, inefficient institutional frameworks, and operational underperformance have persistently hindered the integration of diverse renewable energy sources, ranging from those associated with the conventional system to those reliant on inverter-based systems (Onuh et al., 2024).

In this context, this study aims to investigate the integration of renewable energy in Nigeria's power sector by investigating long-term patterns of renewable electricity generation across various types and configurations of renewable energy systems (on-grid and off-grid systems), assessing the operational performance of renewable energy systems via capacity-generation relationships and utilization patterns. This study contributes to theoretical knowledge by offering a comprehensive analysis of the overall performance of renewable energy operations within the Nigerian power system, and evaluating the effectiveness of renewable energy integration in a weak-grid context.

## **2. Literature Review**

### *2.1 Conceptualizing Renewable Energy Integration in Nigeria*

Renewable energy integration is an ongoing and comprehensive process of adjusting power system design, operation, and governance, rather than a one-time increase in generation capacity (IEA). Effective integration into a power system requires a system capable of matching the variable supply and demand in real time (Goyal & Vadhera, 2024). Initial integration studies focused on technical solutions such as improved forecasting methods, flexible dispatching, expanded grid interconnections, and the availability of responsive reserve capacity (Jennifer Leisch & Jaquelin Cochran, 2015).

However, in more recent publications, flexibility has been conceived as an intrinsic system characteristic, present across generation, transmission, distribution, and institutional coordination,

rather than just a “technical add-on” (Lund et al., 2015). In the Nigerian context, the challenge of renewable energy integration goes beyond simply increasing grid megawatts. Instead, it pertains to the grid's capacity, grid stability, and market institutions and regulations to support the integration of inverter-based renewable energy (Ohiri et al., 2025). Therefore, incorporating renewable energy sources in Nigeria is not only an environmental necessity, but also a regulatory, developmental, and technical imperative.

Nigeria's poor technical grid conditions significantly limit the amount and placement of renewable energy that can be integrated (Anyago, 2024). This is because the power grid has weakened after years of inadequate investment. Such weaknesses hinder the integration of inverter-based renewable technologies owing to low grid strength, which causes voltage instability (Sanni et al., 2024). Empirical evidence indicates that the constraints on the integration of renewables in Nigeria are location-dependent, with points of connection having lower electrical strength that hinders the operation of renewables regardless of capacity.

These studies revealed that optimally designed combinations of renewable energy sources can improve small-signal stability, even under structurally weak grid conditions (Ugwoke et al., 2024).

## *2.2 Overview of Renewable Energy Development in Nigeria*

Nigeria's wealth in natural resources has been widely discussed in several studies. However, these resources have not been fully integrated into the national grid to achieve dependable, fast, and even electricity distribution (Babanyara & Saleh, 2010). Traditionally, large hydropower projects have dominated grid-connected renewable electricity generation. In Nigeria, large hydropower plants constitute the core of the renewable energy supply. However, in recent years, there has been rapid growth in decentralized renewable systems, such as off-grid and mini-grid solar photovoltaics. The trend in Nigeria's renewable energy development is now shifting toward expanding decentralized technologies that enable quicker access to electricity in unconnected areas (Nta et al., 2024).

Empirical evidence indicates that the solar market is the most active in Africa, driven by mini-grid and off-grid solar markets, particularly in areas where grid access is constrained (World Bank Group, 2024). The off-grid solar energy system was previously considered a peripheral option for rural electrification. However, it is currently a major means of accessing energy and effective energy use, particularly when financial mechanisms and quality assurance systems have been established (Nkalo, 2025). To support the growth of renewable energy, Nigeria has introduced various tools (Sambo, 2009). For example, the Electric Power Sector Reform Act of 2005 created the Nigerian Electricity Regulatory Commission and enabled the use of renewable energy feed-in tariffs (Bungane, 2015; NERC). Despite these policy measures, regulatory ambiguity and inconsistent enforcement have damaged investor confidence and slowed project implementation. The overlapping mandates of various government agencies complicate policy coordination. Consequently, it has not led to an equal increase in the operational levels of renewable electricity generation, as envisioned in national strategies and targets.

In addition to the rapid development and expansion of solar energy systems, hydropower plays an

important role, especially as a flexible source; however, its future development must be carefully planned, and financing is needed for future expansion and development (Aliyu et al., 2015; IEA, 2021). The vast potential of biomass energy has been discussed in various studies, each highlighting limitations such as residue supply and price competition, which can affect large-scale biomass operations (Aliyu et al., 2015; Omer, 2016; Schipfer et al., 2022). Even with the availability of considerable feedstock, this is due mainly to supply chain issues, demand competition, and costs (Edomah, 2019). Collectively, the extant literature shows that the development of renewable energy in Nigeria faces more barriers to system integration than to resource availability (Adeyeye & Mbohwa, 2026). Despite these policies, empirical evidence shows that renewable energy generation remains constrained by system challenges, even with additional capacity expansion. This defeats the purpose of achieving meaningful integration.

These studies have established that policies have been enacted nationwide to encourage renewable energy development, although some hiccups hinder their full implementation. Decentralized solar power has proven to be a more viable energy-generating option, whereas hydropower requires further careful planning, and bioenergy project scaling remains structurally challenging (Ozoegwu et al., 2017). This means that renewable energy development in Nigeria is more like an integration problem that connects finance, stable policies, and technology rather than just a choice among hydro, solar, wind, and biomass. To achieve sustainable development for the Nigerian population, integrating and developing renewable energy will reduce poverty and promote productivity in businesses in the country (Edomah, 2016).

### **3. Methodology**

This study employed a combination of longitudinal and ex post facto research designs to evaluate renewable energy integration in Nigeria's power sector from an operational performance perspective. The longitudinal design applied in this study was first initiated by Lewis Terman in one of his studies on gifted children in 1920 (Hastorf, 1997), and was used to analyze the changes in patterns and developments of renewable energy generation and operational performance trends in the Nigerian energy sector over a ten year period (2014-2024). This method supports the objective of evaluating performance trends and future integration opportunities. The use of ex post facto design, also known as 'after-the-fact' research, is suitable because it enables a systematic review of the data without manipulating system variables (Carlos Nunes Silva, 2010). This approach enables a thorough examination of the operational performance of renewable energy within the power system by conducting a statistical comparison between renewable energy outlets and gas-fired outlets. The analytical framework of this study is a combination of descriptive statistics, time series trend analysis and inferential statistical testing. Focusing on the capacity-generation relationship over time enables a direct assessment of operational performance and the extent of renewable energy underutilization in a weak-grid context (IEA, 2013). As a result, this methodological approach is instrumental in examining

whether the underperformance of the integrated renewable energy is attributed to the scarcity of resources or from limitations within the system and grid infrastructure, thereby directly addressing the study's research objectives.

### 3.1 Data

The data used for this study were obtained from both official Nigerian power sector websites and the recognized international energy database. The key dataset on the operational performance of integrated renewable energy in the power system was obtained from the Nigerian Electricity Regulatory Commission (NERC), whereas the International Renewable Energy Agency (IRENA) provided information on the historical trends of various renewable energy sources from 2014-2024 (IRENA, 2025). The data cover renewable energies from biofuels (bioenergy), renewable hydropower and solar photovoltaics and includes system types such as on-grid and off-grid systems. Since the energy sector in Nigeria operates with variety of energy outlets, data on operational performance were obtained from these various energy outlets, some of which were strictly related to renewable energy generation.

### 3.2 Data Analysis

This study employed a comprehensive analysis process to measure the performance of renewable energy outlets and energy generation over the past decade. First, the operational performance of the energy sector was evaluated through descriptive statistics, which present the average energy generation via charts.

To examine the performance of renewable energy integrated into the national grid and if it reflects existing technological inadequacies or broader system constraints, an independent sample t-test was applied to compare the performance metrics between renewable energy and gas generation in the power system. Given the unequal sample sizes and variance structures between the datasets, the t-test was appropriate. This was conducted at the 95% confidence level.

To analyze trends in renewable energy generation, time-series forecasting was conducted via the exponential smoothing method (Hyndman, R. J., & Athanasopoulos, G., 2021). This method was particularly effective for analyzing and predicting energy generation for the coming years. The exponential smoothing model employed in this study is represented in equation (1):

$$\hat{y}_{t+1} = \alpha y_t + (1 - \alpha)\hat{y}_t \quad (1)$$

where; is the forecasted renewable energy for the next period

$y_t$  is the actual value in the current year

$\hat{y}_t$  is the forecasted value for the current year

where is the smoothing constant (set at 0.3 to balance responsiveness and stability).

The smoothing constant was chosen to accurately reflect medium-term trend dynamics while reducing the overreaction to short-term fluctuations.

#### 4. Results & Discussion

This section presents and interprets the empirical findings on the operational performance of renewable energy in Nigeria as well as energy generation patterns and supply. Emphasis is placed on relationships, structures, and constraints rather than expansion.

##### 4.1 Renewable Energy Operational Performance

To evaluate the operational performance of renewable energy generation, on the basis of data gathered from various outlets, we empirically compared the energy generated by renewable energy outlets with that of outlets generating gas. This will provide a clear idea of whether renewable energy outlets are more highly operational than gas outlets or not. To achieve this, we tested the following hypothesis:

$H_0$ : There is no significance difference in total energy generation between RE outlets and gas outlets

**Table 1. T Test on RE and Gas**

	<i>RE</i>	<i>Gas</i>
Mean	210.63	105.67
Variance	15666.26	12035.24
Hypothesized Mean Difference	104.97	
df	4	
t Stat	4.42	
P(T<=t)	0.04	
t Critical two-tail	2.78	

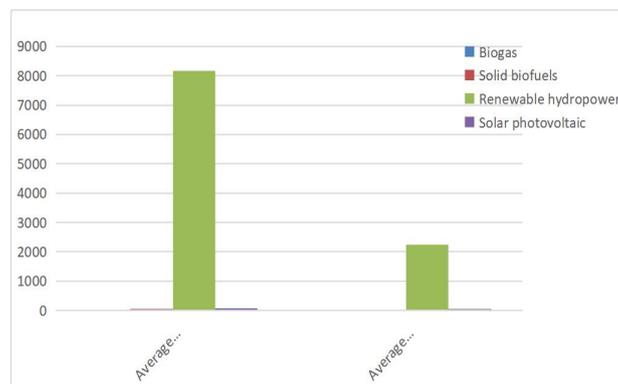
The results in Table 1 show that renewable energy has greater operational performance than gas in terms of energy generation capacity. The average renewable energy generation by an outlet was estimated to be 210.63 GWh, whereas the average gas generation by an outlet was estimated to be 105.67 GWh. This accounted for a mean difference of 104.97 GWh. This test is significant since the p-value (0.04) is less than the criterion (p-value  $\leq 0.05$ ); hence, the hypothesis stated above is rejected. This means that there is a significant difference in the total energy generation between RE and gas outlets, such that there is a greater operational performance in RE generation than in gas generation in terms of average energy generation. To affirm the rejection of the hypothesis, the t-stat value (4.42) is greater than the t-critical value (2.78), which supports the test results.

Table 2 and Figure 1 show that, on average, there is a significantly greater generation of renewable hydropower than biogas, solid biofuels, and solar photovoltaics. Additionally, for installed capacity, renewable hydropower has a very high installed capacity compared with biogas, solid biofuels, and solar photovoltaics, which is an indication of high operation performance for on grid renewable hydropower, and the high dependency on renewable hydropower in Nigeria over the past 10 years. Solar photovoltaic and solid biofuels are also in use, although their use is relatively low in the energy

sector. However, biogas is the least commonly used renewable energy source.

**Table 2. Average Renewable Energy Generation and Installed Capacity by Technology**

Technology	Average Yearly Generation for the past 10 years (GWh)	Average Installed Capacity for the past 10 years (GWh)
Biogas	0.08	0.02
Solid biofuels	40.95	14.3
Renewable hydropower	8173.48	2247.16
Solar photovoltaic	64.54	45.75



**Figure 1. Average Renewable Energy Generation and Installed Capacity by Technology**

The performance indicators, clearly indicate that the integration of renewable energy in Nigeria is unbalanced, with hydropower dominating both installed capacity and electricity generation. This observation is consistent with previous studies that have established that large-scale hydropower has been and remains one of Nigeria’s dominant renewable energy sources for electricity supply (IRENA, 2023; Oyedepo, 2012). Similarly, in many other sub-Saharan African electricity systems, hydropower predominates the renewable energy supply (Simon Trace, 2019). The large difference between the existing hydro capacity and electricity generated, as shown in Figure 1, supports existing research indicating that renewable energy underperformance is explained mainly by operational issues rather than resource availability (Ikejemba et al., 2017). Even with the high electricity generated by hydro energy, there is still a shortage in electricity supply from the power sector, which is due to the state of the grid system and infrastructure. Research on the global challenges of weak grid infrastructure has revealed that congestion, hydrological factors, and system flexibility issues hinder the full exploitation of renewable energy capacities (Branding, 2025). The minor contributions of solar photovoltaics, solid biofuels, and biogas observed in this study validate existing research, indicating that renewable energy diversification in Nigeria is constrained by integration issues rather than technology availability.

We further evaluate the performance of the energy system on the basis of average yearly energy generation for on-grid and off-grid energy.

**Table 3. On-grid vs Off-grid Performance**

Type	Average Yearly Generation for the past 10 years (GWh)	Average Installed Capacity for the past 10 years (GWh)
Off-grid energy	57.03	34.33
On-grid energy	8223.01	2272.9

Table 3 shows the dominance of on-grid energy systems over off-grid energy systems. For both energy generation and installed capacity, there is greater operational performance in terms of on-grid energy than in terms of off-grid energy. This phenomenon is likely attributed to Nigeria’s overreliance on hydropower generation.

This finding also supports earlier assessments of Nigeria’s electricity system structure (Oseni, 2011). On the other hand, the efficiency of off-grid renewable energy systems highlights empirical studies that indicate that decentralized energy solutions can outperform centralized generation in weak-grid environments (IEA, 2025; IRENA, 2021). Previous research on deploying mini-grids and off-grid solar systems in Nigeria has demonstrated that reduced reliance on transmission infrastructure allows decentralized systems to deliver more reliable and efficient electrical power (Ohiare, 2015), reinforcing the emerging view that off-grid renewable energy systems are inherently more resilient than centralized grid expansion.

*4.2 Energy Generation Performance Over Time*

In this section, we historically evaluate the energy generation performance across different energy sources from 2014-2024. Like biogas, solid biofuels, renewable hydropower, and solar photovoltaics. This is shown in Table 4.

**Table 4. Trend analysis on Energy Generation**

Year	Biogas	Solid biofuels	Off-grid Renewable hydropower	On-grid Renewable hydropower	Off-grid Solar photovoltaic	On-grid Solar photovoltaic
2014	0.04	6.37	3.13	6143.72	5.86	0.44
2015	0.04	6.37	3.13	6420.19	15.66	7.83
2016	0.09	9.87	3.13	8147.25	19.91	12.04
2017	0.09	13.3	3.13	7743.63	27.87	13.47
2018	0.09	15.18	3.13	7691.70	34.42	13.47

2019	0.09	11.56	3.13	8430.05	52.27	24.72
2020	0.09	25.53	3.13	7868.79	75.63	39.99
2021	0.09	46.05	3.13	9150.68	99.08	64.52
2022	0.09	44.44	3.13	9232.22	136.75	70.38
2023	0.09	46.54	3.13	9423.28	182.81	85.15
2024	0.09	45.65	3.13	9622.32	198.57	96.27

Table 4 shows that there has been a consistent growth trend in the use of solid biofuels, on-grid renewable hydropower, off-grid solar photovoltaics, and on-grid solar photovoltaics. However, biogas and off-grid renewable hydropower have remained stagnant over the years. This indicates that decentralized solar energy is Nigeria's fastest-growing renewable energy sector.

This aligns with previous studies on the factors driving solar PV development in developing economies. These factors include the costs of solar PV technology, its modular deployment nature, and unmet electricity demand, as noted by the International Renewable Energy Agency (IRENA, 2023c). The gradual expansion of on-grid solar photovoltaics matches other weak grid scenarios, where issues related to connectivity, curtailments, and flexibility constraints hinder large-scale solar power integration. The moderate and variable growth of solid biofuels and the stagnant growth of biogas production corroborate previous findings regarding the challenges associated with bioenergy production in Nigeria. These challenges include supply issues, competing demands for bioenergy feedstocks, and poor institutional support.

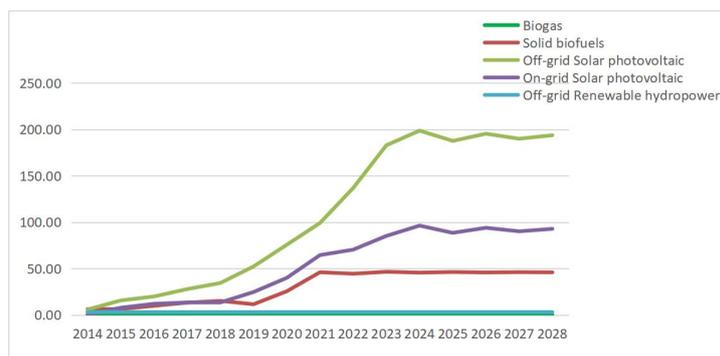
#### 4.3 Forecasting Renewable Energy Generation

Using the exponential smoothing technique, various types of renewable energy generation were forecasted for the next three years. The forecasted values appear to be consistent for the next three years, with on-grid renewable hydropower dominating the energy sector, as shown in Table 5 and Figure 2.

**Table 5. Time-Series Forecasting on Energy Generation**

Year	Biogas	Solid biofuels	Off-grid Solar photovoltaic	On-grid Solar photovoltaic	Off-grid Renewable hydropower	On-grid Renewable hydropower
2014	0.04	6.37	5.86	0.44	3.13	6143.72
2015	0.04	6.37	15.66	7.83	3.13	6420.19
2016	0.09	9.87	19.91	12.04	3.13	8147.25
2017	0.09	13.3	27.87	13.47	3.13	7743.63
2018	0.09	15.18	34.42	13.47	3.13	7691.70
2019	0.09	11.56	52.27	24.72	3.13	8430.05

2020	0.09	25.53	75.63	39.99	3.13	7868.79
2021	0.09	46.05	99.08	64.52	3.13	9150.68
2022	0.09	44.44	136.75	70.38	3.13	9232.22
2023	0.09	46.54	182.81	85.15	3.13	9423.28
2024	0.09	45.65	198.57	96.27	3.13	9622.32
2025	0.09	46.27	187.54	88.49	3.13	9482.99
2026	0.09	45.84	195.26	93.94	3.13	9580.52
2027	0.09	46.14	189.86	90.13	3.13	9512.25
2028	0.09	45.93	193.64	92.80	3.13	9560.04

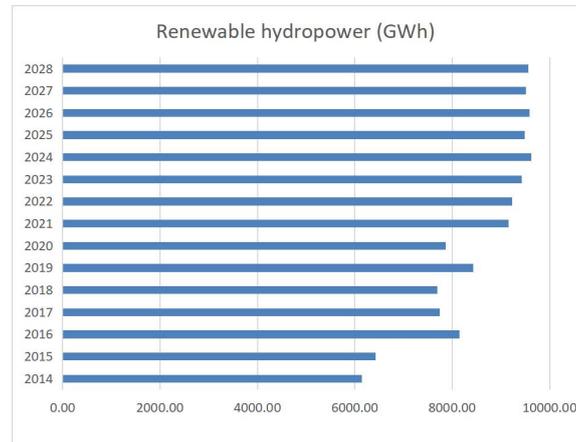


**Figure 2. Forecasted Renewable Energy Generation**

Figure 2 shows that energy generation has been relatively consistent since 2023 and appears to continue in the same line from 2026 to 2028. The consistent generation of renewable energy suggests that for the energy sector to evolve positively in terms of performance, certain policies must be in place.

The projected disparities in energy generation performance could be associated with increasing vulnerabilities and climate and resource variability. Additionally, the persisting marginal growth in bioenergy technologies is in line with earlier findings that classified bioenergy technologies as structurally constrained in Nigeria.

Figure 3 indicates that the growing trend of integrated renewable hydropower systems is gradually dominating Nigeria’s renewable energy market. This could be because there is sufficient flow and availability of water. The results show that hydropower expansion is experiencing a gradual progression, with capacity increasing from approximately 6,144 GWh in 2014 to approximately 9,622 GWh in 2025. Using the exponential smoothing technique, it is estimated that this growth will appear to be constant between 2026 and 2028.



**Figure 3. Renewable Hydropower Generation**

However, its growth shows signs of deceleration, which can be due to system limitations, such as rainfall variability. Bioenergy technologies are also experiencing low adoption rates, primarily because of the limited expansion of solid biofuels and biogas. From an operational perspective, the rapid expansion of off-grid solar energy creates new opportunities for improved access to electricity but also introduces challenges in system operation and management, as well as interoperability with a structurally weak national grid. Even as hydropower plays a balancing role in the system, its overall efficiency is limited by congestion in the transmission network and its inherent seasonal intermittency.

### 5. Recommendation and Conclusion

This study and analysis provide clearer insight into the operational performance of Nigeria's integrated renewable energy. These findings reveal that, despite Nigeria's abundant renewable energy resources, the electricity generated and supplied from integrated renewable energy sources remains insufficient to satisfy the country's high electricity demand. This inadequacy is attributed to systemic inefficiencies rather than limitations in capacity, which hinder their effective utilization. Hydropower remains the primary form of renewable energy generation; however, it faces challenges such as transmission issues and outdated infrastructure. Although hydropower contributes to balancing the national grid, the results indicate that it lacks the ability to drive growth within the renewable energy sector. Additionally, the rapid growth of decentralized solar energy, driven by the technology's suitability for areas with limited grid services and its ability to serve the country's underserved or unserved population, shows that solar photovoltaic technology is the most dynamic component of Nigeria's renewable energy sector. Furthermore, the rapid growth of off-grid systems poses challenges, including the management of system intermittency and limited grid connectivity. Bioenergy remains the least dynamic segment of Nigeria's renewable energy sector, with low and inconsistent production levels posing ongoing challenges.

Evaluating the operational performance of these renewable energy resources integrated within the

Nigerian power sector is crucial for recognizing that the integration of renewable energy in Nigeria must be accompanied by a comprehensive power sector reform agenda. This is essential for addressing the inefficiencies and constraints within the institutional environments of the power sector.

Moreover, Nigeria's renewable energy policy should shift from a capacity expansion approach to an integration approach that emphasizes the efficient use of existing capacity rather than expanding power plant capacity. Investments in the power grid should be prioritized to reduce system congestion.

In conclusion, the results confirm that the renewable energy sources integrated into the national power system are underperforming, which is not due to resource availability. The persistent gap between the installed capacity and actual electricity generation underscores the importance of grid preparedness and operational efficiency in addressing this issue.

### *5.2 Limitations and Future Research Direction*

This research employs only secondary, exclusively quantitative methods, which makes it challenging to fully understand the dynamic constraints and decision-making in operational settings. Future studies can build on this research by incorporating primary data, simulations, and grid dispatch methodologies to examine renewable-energy integration in various policy and infrastructure contexts. Additionally, climate risk modeling and storage deployment will improve understanding.

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### **Conflict of interest declaration**

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 paper.

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### **Ethical Statement**

We declare that this submission follows the policies outlined in the Guide for Authors.

### **Data Availability**

The data will be made available upon request.

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