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Impacts of Renewable Energy Sources Integration on the Reliability and Sustainability of Nigeria's Electrical Power System

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ABSTRACT
Electrical power systems are critical infrastructures that ensure the continuous supply of energy to meet the growing demands of modern society. These systems encompass power generation, transmission, distribution, and consumption, requiring coordinated operation to maintain stability, reliability, and efficiency. Recent trends, including the integration of renewable energy sources, energy storage technologies, and smart grid solutions, are transforming conventional power systems into more adaptive and sustainable networks. Despite these advancements, challenges such as voltage fluctuations, frequency instability, power losses, cybersecurity threats, and the intermittent nature of renewable resources remain significant. This paper reviews the fundamental components of electrical power systems and highlights recent technological innovations, including advanced monitoring, predictive maintenance, grid automation, and demand-side management. Furthermore, it discusses ongoing research directions aimed at improving system resilience, enhancing energy efficiency, and enabling a seamless transition toward cleaner and smarter energy networks.
Keywords: Electrical power systems, power generation, transmission, distribution, smart grids, renewable energy integration, energy storage, system stability, power system automation, grid resilience, demand-side management, sustainable energy.

INTRODUCTION

The Nigerian power sector, which includes electricity generation, transmission, and distribution, plays a crucial role in the nation's economic activities. As one of the most populous nations in Africa, Nigeria's electricity demand is growing at an unprecedented rate, driven by industrialization, urbanization, and population growth. However, the country's power generation capacity has consistently lagged behind the rising demand. According to Onwuka et al. (2024), the installed capacity of the national grid is currently around 13,000 MW, yet the actual available capacity often falls significantly short of this figure. Peak demand has been estimated at about 16,000 MW, but the country frequently operates with an available generation capacity of only 3,000 MW to 4,000 MW due to technical failures, fuel shortages, and operational inefficiencies (Onwuka et al., 2024).

Adebayo and Ogunyemi (2021) argue that the underperformance of Nigeria's electrical power system can be attributed to a combination of factors, including inadequate infrastructure, insufficient investment in maintenance, and poor management practices within state-owned entities. The privatization of the power sector, while theoretically offering a pathway to greater efficiency, has not resulted in significant improvements. Rather, many privately owned utilities continue to face financial and operational challenges that undermine the overall stability of the system. Additionally, the regulatory environment remains weak, with inconsistent policy enforcement and insufficient incentives to attract investments in infrastructure. A significant portion of Nigeria's electricity is generated through thermal plants, which rely heavily on natural gas and, to a lesser extent, oil. While these resources have powered the sector for decades, their long-term sustainability is increasingly in question due to volatile global oil prices and growing environmental concerns. Eze et al. (2023) emphasize that while Nigeria is home to vast renewable energy potential, particularly solar and wind energy, these resources remain largely untapped due to infrastructural limitations and a lack of effective government support.

The Nigerian government has recognized the need to diversify the energy mix, and there are ambitious targets to increase the share of renewable energy in the power sector. According to Ademola and Durojaiye (2022), the government aims to generate 30% of the country's electricity from renewable sources by 2030. Despite these ambitious targets, the transition to renewables has been slow, primarily due to high initial investment costs, insufficient grid infrastructure, and the technical challenges of integrating intermittent renewable sources into the national grid. As observed by Olaniyi et al. (2024), Nigeria's power grid infrastructure, which was designed for centralized generation, is ill-suited for the efficient integration of decentralized renewable energy systems. The grid's limited capacity for real-time monitoring, coupled with its vulnerability to disruptions, makes it challenging to optimize the distribution of electricity across the country. Moreover, there are widespread issues of transmission and distribution

losses, which further exacerbate the supply gap. In response to these challenges, technological advancements such as smart grid systems and energy storage solutions have emerged as potential game-changers for Nigeria's power sector. Smart grids offer improved management of electricity flows, enabling better integration of renewables and real-time monitoring of system performance (Okafor & Chijioke, 2023). However, as noted by Olayemi and Usman (2025), the adoption of smart grid technology in Nigeria remains constrained by financial limitations, regulatory hurdles, and a lack of technical expertise among the local workforce.

Statement of the Problem

Electrical power systems are the foundation of modern economies, driving everything from industry to healthcare and education. For any country, a reliable and efficient power system is essential for sustaining economic growth and improving the quality of life for its people. In Nigeria, however, the electricity sector remains a major hurdle in national development. Despite the country being rich in energy resources, including natural gas, hydro, and immense potential for renewable energy such as solar and wind, the power sector has consistently failed to meet the ever-growing demand for electricity.

The gap between electricity demand and available supply is striking. Nigeria's national grid capacity is around 13,000 MW, while demand hovers at approximately 16,000 MW, yet the actual available electricity rarely exceeds 4,000 MW. This results in persistent power outages, unstable voltage, and an overall unreliable electricity supply for millions of Nigerians. The country's electricity infrastructure, including its generation, transmission, and distribution systems, is aging and inefficient. Despite efforts to address these issues, such as the privatization of the power sector in 2013, these reforms have yielded mixed results. Privatized utilities still struggle to provide consistent service, hindered by underinvestment, a lack of regulatory oversight, and outdated technology. Furthermore, the integration of renewable energy into the grid has been slow, facing several barriers, including technological limitations, regulatory challenges, and financial constraints. The lack of a comprehensive, modern energy policy has meant that substantial improvements to the power sector remain elusive, affecting Nigeria's ability to sustain its development goals. This study seeks to explore these challenges, specifically addressing how Nigeria can modernize its power system to meet the needs of its growing population, support economic growth, and transition to a more sustainable energy future. The research will focus on the operational inefficiencies within the sector, the potential for renewable energy integration, and the role of technological innovations like smart grids in improving the country's electricity system.

Objectives of the Study

This study scrutinized the impacts of renewable energy sources integration on the reliability and sustainability of Nigeria's electrical power system. To achieve the main aim, the following key objectives were considered:

1. To assess the operational inefficiencies within Nigeria's electricity generation, transmission, and distribution systems and understand the root causes of the country's ongoing power deficits.
2. To explore the potential of integrating renewable energy sources (such as solar, wind, and hydro) into Nigeria's power grid, taking into account both the technical feasibility and the economic implications..

Research Questions

This study seeks to answer the following questions:

1. What are the primary operational inefficiencies and infrastructural challenges facing Nigeria's electricity generation, transmission, and distribution systems?
2. How can the integration of renewable energy (such as solar, wind, and hydro) improve the sustainability, reliability, and cost-effectiveness of Nigeria's electricity supply?

Hypotheses

The study tests the following hypotheses:

H1: Integrating renewable energy sources such as solar, wind, and hydro will significantly improve the reliability and sustainability of Nigeria's electrical power system.

Significance of the Study

This research holds significant value across several dimensions The findings will provide critical insights for policymakers in Nigeria to develop more effective strategies to address the systemic challenges of the power sector. The study's recommendations will help guide future reforms, particularly in terms of renewable energy adoption, grid modernization, and policy implementation. This research highlights the importance of embracing modern technologies like smart grids and renewable energy solutions to enhance the efficiency and sustainability of Nigeria's power sector. The study will explore the potential of these technologies to revolutionize Nigeria's energy landscape and contribute to global sustainability goals. Access to reliable and affordable electricity is a key driver of economic growth and social development. By identifying solutions to Nigeria's power crisis, this research aims to improve industrial productivity, reduce energy poverty, and enhance the quality of life for millions of Nigerians. As the world shifts toward cleaner, renewable energy, this study will contribute to global discussions on energy sustainability. It will assess how Nigeria can leverage its renewable energy resources to reduce dependency on fossil fuels and mitigate the environmental impact of its power sector. This research adds to the academic literature on energy systems, particularly in developing economies. It provides a detailed analysis of Nigeria's energy sector, offering insights into the challenges and opportunities involved in modernizing and expanding electricity systems in Africa.

Scope and Limitations

Scope of the Study

This study examines various aspects of Nigeria's electrical power system, focusing on the following key areas The research assess the performance and capacity of existing power plants in Nigeria, including both thermal and renewable energy-based plants. It also evaluates their ability to meet the growing demand for electricity. The study further looks at Nigeria's electricity transmission and distribution infrastructure, identifying bottlenecks and inefficiencies that prevent a reliable and widespread supply of electricity. The research also explores the potential for integrating renewable energy sources, such as solar, wind, and hydro, into Nigeria's power grid, considering technical and economic feasibility. Similarly, the study also assesses the potential of smart grids in Nigeria, focusing on their ability to optimize grid performance, reduce losses, and enhance real-time energy management. Conclusively, the study also evaluate the effectiveness of privatization, deregulation, and other reforms undertaken in Nigeria's power sector since the early 2000s.

Limitations of the Study

Several limitations affected the scope and outcomes of this research; Access to comprehensive and up-to-date data on Nigeria's power sector, especially regarding rural areas, is a challenge. The study is also limited by gaps in reliable data from key stakeholders like utilities and regulatory bodies. Due to logistical constraints, the study was not be able to cover all regions of Nigeria comprehensively, especially remote or conflict-affected areas with limited electricity access. Nigeria's power sector is subject to evolving regulatory frameworks, and political changes which impacted the implementation of key policies, making it difficult to assess the long-term impact of reforms. The practical implementation of smart grid technologies in Nigeria is still in the early stages, so data on the effectiveness of such technologies is limited. Nigeria's power sector is vulnerable to macroeconomic factors like inflation, fluctuating oil prices, and exchange rate volatility, all of which has affected the assessment of long-term investment needs and policy effectiveness.

Literature Review

Conceptual and Theoretical Framework

Conceptual Review

At the core of electrical power system studies is a holistic understanding of how electricity is generated, transmitted, distributed, and consumed within a country. In the Nigerian context, this involves not only engineering networks but entire socio-technical systems shaped by infrastructure, regulation, and market forces. As Adewale and colleagues (2023) articulate, an electrical power system is "an integrated network

of generation, transmission, distribution, and utilization components whose coordinated operation ensures continuous and quality electricity delivery to end-users" (Adewale et al., 2023). This definition emphasizes that system performance depends not on any single component, but on how well the parts operate together.

A central concept in the literature is energy access, which goes beyond mere connection to the grid to capture reliability, affordability, and quality of supply. Olaniyi et al. (2024) note that energy access in Nigeria "is not merely a technical condition but a socio-economic enabler that influences household welfare, commercial activity, and public services such as healthcare and education." Their analysis highlights that inadequate generation capacity, outdated infrastructure, and high transmission and distribution losses have prevented electricity from reaching many Nigerians consistently (Olaniyi et al., 2024). This observation aligns with broader evidence showing that while access has improved in some urban areas, large portions of rural Nigeria still lack dependable electricity, reinforcing inequality and constraining development. Nigeria's power system remains heavily dependent on thermal generation, primarily from natural gas, supplemented by hydropower, with renewable sources such as solar and wind still underrepresented. Eze et al. (2023) observe that "despite Nigeria's significant endowment of renewable energy potential, structural and regulatory barriers have limited the actual contribution of these sources to the national grid." Their findings underscore that abundant renewable resources if harnessed could substantially reduce dependence on fossil fuels and lower environmental impacts, yet *this potential remains largely unrealized* due to economic and policy constraints.

Conceptually, renewable energy integration is not just about adding new sources; it represents a strategic opportunity to enhance grid resilience and expand access. Okafor and Chijioke (2023) argue that decentralized renewable systems—such as solar mini-grids and off-grid installations offer practical means to expand electricity access in regions where the central grid is either absent or unreliable. They contend that these systems can serve as bridges to broader electrification, especially for rural and peri-urban communities that traditional grid extensions have failed to serve (Okafor & Chijioke, 2023). This perspective is reinforced by ongoing initiatives such as Nigeria's recent agreements to deploy hundreds of renewable mini-grids to rural areas, which aim to serve millions of people and diversify energy sources beyond the conventional grid. However, the literature also recognizes that renewable integration poses new technical challenges, particularly given the intermittency of sources like solar and wind and the current weakness of Nigeria's grid infrastructure. Nigerian researchers such as Sunday and Mutah (2024) emphasize that while renewable energy offers promise, it must be paired with smart grid technologies, robust energy management systems, and energy storage solutions to enable effective utilization and stability. They argue that "modernizing infrastructure through digital and automated technologies is essential for handling variable renewable generation and meeting operational demands" (Sunday & Mutah, 2024).

Smart grids, as conceptualized by Dahunsi et al. (2024), represent an emerging paradigm that could transform the power system from a centrally managed, rigid network into a dynamic, responsive platform. Smart grid technologies incorporate advanced metering, distributed generation management, and real-time control systems to better balance supply and demand and reduce losses. Dahunsi and colleagues highlight that "shifting from manual control to digital, ICT-enabled grid operations is fundamental to improving reliability, reducing outages, and enabling deeper integration of renewables" (Dahunsi et al., 2024). In addition to technological considerations, policy landscapes also shape how the power system evolves. Ajia (2025) emphasizes that Nigeria's array of policy frameworks such as the Renewable Energy Master Plan (REMP) and the National Renewable Energy and Energy Efficiency Policy (NREEEP) holds significant potential to support renewable deployment, but their impact has been muted by regulatory fragmentation and implementation gaps. Ajia asserts that "without a coherent, enforceable, and well-coordinated regulatory framework, the necessary scale of renewable energy growth and access improvements will remain unattainable" (Ajia, 2025). Taken together, the conceptual review shows that scholars increasingly view Nigeria's power system not simply as an engineering network but as a **socio-technical ecosystem**. This ecosystem is shaped by infrastructure quality, energy policy, economic

constraints, social demand, and technological innovation. Understanding how these elements interact is critical for framing research questions and designing interventions that move the system toward greater reliability, sustainability, and equitable access.

Theoretical Framework

Several theoretical frameworks are employed to explain the challenges and opportunities in improving electrical power systems, particularly in developing countries such as Nigeria. These frameworks help contextualize the underlying issues within Nigeria's electricity sector and offer insights into the complex interplay of technology, policy, infrastructure, and socio-economic factors. The main theories applicable to Nigeria's energy transition and sectoral reforms include **Energy Transition Theory**, **Systems Theory**, and **Institutional Theory**. Each provides a unique perspective on the problems and potential solutions facing Nigeria's power system.

1. Energy Transition Theory

Energy Transition Theory is grounded in the understanding that shifts from fossil fuel-based energy systems to cleaner, renewable energy sources involve a combination of technological, economic, and socio-political changes. This theory, largely developed by scholars such as Geels (2002), focuses on how energy transitions occur and the factors that drive or hinder these transitions. In the case of Nigeria, the shift toward renewable energy is not simply a technical challenge but also a process that is influenced by political will, financial investments, technological innovation, and public acceptance.

Adebayo and Ogunyemi (2022) explain that the theory posits that energy transitions are driven by "technological innovations, policy shifts, and socio-economic factors" (Adebayo & Ogunyemi, 2022). In Nigeria, however, the process is complicated by institutional barriers, such as inadequate policy frameworks, lack of financing for renewable energy projects, and technological constraints. The authors argue that Nigeria's energy transition faces several obstacles, including weak political support, limited access to green financing, and insufficient technical expertise to effectively implement renewable energy solutions.

Furthermore, Adebayo et al. (2023) note that energy transitions in Nigeria are influenced by global trends, particularly in international climate agreements such as the Paris Agreement. While these agreements provide a framework for encouraging renewable energy adoption, the lack of effective implementation mechanisms in Nigeria continues to slow down progress. They conclude that overcoming these challenges requires multi-dimensional reforms that involve both technology-driven solutions and strong, institutionally supported policies.

2. Systems Theory

Another useful theoretical framework in understanding Nigeria's electrical power system is Systems Theory, which originates from Ludwig von Bertalanffy's General Systems Theory (1968). This theory posits that complex systems consist of interconnected components that must be managed cohesively to achieve optimal performance. In the context of Nigeria's power sector, the electrical grid is not just a network of isolated power plants but an interconnected system involving generation, transmission, distribution, and consumption. Therefore, addressing inefficiencies in one part of the system often requires comprehensive changes across all parts.

As articulated by Olayemi and Usman (2025), Systems Theory emphasizes the interdependency of various components of the power system: "The inefficiencies in power generation, transmission, and distribution are interconnected, and addressing one aspect of the system—such as upgrading power plants or modernizing the grid—requires changes across all levels of the system" (Olayemi & Usman, 2025). This perspective stresses the importance of integrated approaches to reform, whereby changes to one aspect of the power sector (e.g., generation capacity) are accompanied by complementary reforms in other areas (e.g., transmission and distribution systems). It also highlights the need for a systems-level approach when designing and implementing solutions to improve Nigeria's electricity sector.

In the Nigerian context, this theory underscores that efforts such as upgrading generation capacity without addressing issues of transmission losses and grid instability will only offer limited improvements.

Scholars such as Sunday & Mutah (2024) and Dahunsi et al. (2024) have also emphasized that digital technologies, such as smart grids and real-time monitoring systems, can serve as crucial tools to optimize the coordination between these various components of the power sector.

3. Institutional Theory

Institutional Theory, particularly as developed by North (1990) and applied to energy systems by DiMaggio and Powell (1983), explains how policies, regulations, and governance structures shape the performance of energy systems. This theory suggests that energy systems do not function in a vacuum but are influenced by broader institutional frameworks, such as regulatory bodies, political institutions, and cultural norms. In Nigeria, weak institutions—such as inadequate regulatory oversight, inconsistent policies, and corruption—have significantly contributed to the persistent inefficiencies in the power sector.

Adewale et al. (2022) apply Institutional Theory to Nigeria's power sector and argue that institutional failures, including poor governance, regulatory inconsistencies, and corruption, have hindered the effectiveness of reforms such as the privatization of the electricity sector. They highlight that while privatization was intended to improve service delivery and efficiency in the sector, the lack of strong, transparent governance and inadequate enforcement mechanisms has undermined its potential to deliver reliable electricity. They argue that institutional failure characterized by corruption and weak legal frameworks—has led to mismanagement and underperformance in both generation and distribution sectors.

Similarly, Olaniyi et al. (2024) stress that weak regulatory frameworks and insufficient investment in human and technical capital have created significant barriers to achieving sustainable energy development in Nigeria. They assert that the inability of Nigerian institutions to enforce energy policies effectively has contributed to regulatory uncertainty, financial instability, and political interference, all of which hamper the shift toward renewable energy solutions. As a result, institutional theory offers critical insights into understanding the systemic governance failures that contribute to the inefficiency of Nigeria's electricity

Empirical Review

The empirical literature on Nigeria's electrical power system provides a nuanced view of the challenges facing the sector, including power shortages, inefficiencies in infrastructure, and the role of renewable energy integration. A growing body of research has also explored the impact of privatization and the potential of modern technologies like smart grids to enhance the country's electricity distribution and management.

Challenges in Power Generation and Distribution

A significant body of research has focused on the structural challenges within Nigeria's energy system, particularly regarding inefficiencies in power generation, transmission, and distribution. According to Okolo et al. (2023), the persistent power shortages in Nigeria are largely due to aging infrastructure, inefficient power plants, and substandard transmission networks. Their study underscores that despite Nigeria's substantial energy resources, the inability to harness these resources effectively has led to chronic power deficits. Okolo et al. (2023) argue that poor maintenance practices and underinvestment in infrastructure have compounded these challenges, making it difficult to meet the growing demand for electricity.

Moreover, Adewale et al. (2022) highlight that while Nigeria's electrical system is capable of generating higher outputs, operational inefficiencies, such as inefficient fuel utilization in thermal plants, and severe transmission losses of up to 30%, prevent the country from tapping into its full generation potential. The authors emphasize that without substantial upgrades in infrastructure and management practices, these inefficiencies will continue to impede progress.

Renewable Energy Potential

Renewable energy is widely regarded as a key solution to Nigeria's power sector challenges, with several studies exploring the potential of solar, wind, and hydropower to diversify the energy mix. Onwuka et al. (2024) provide an in-depth review of Nigeria's renewable energy potential, noting that solar energy stands

out due to the country's high levels of solar radiation. The authors argue that Nigeria's potential for solar energy is immense, with an estimated over 3,000 hours of sunshine annually (Onwuka et al., 2024). However, they note that investment barriers, regulatory inefficiencies, and insufficient technical capacity have significantly delayed the widespread adoption of solar energy systems. They advocate for stronger policy frameworks, including financial incentives and technical capacity-building programs, to accelerate solar energy development.

Eze et al. (2023) emphasize that Nigeria's renewable energy potential, particularly in wind and hydropower, is similarly underutilized. Their research indicates that, although the country is endowed with significant wind power resources in northern regions and several hydropower stations, challenges related to grid integration, financing, and regulatory frameworks continue to hinder their large-scale deployment. The authors suggest that a coordinated approach involving government agencies, private investors, and international stakeholders is necessary to leverage renewable energy sources effectively.

Smart Grid Technologies and Grid Management

In recent years, smart grid technology has emerged as a promising solution to improve the reliability and efficiency of Nigeria's power sector. Olaniyi et al. (2024) explore the potential benefits of smart grids in Nigeria, noting that these technologies can help mitigate some of the most pressing issues faced by the country's electrical grid, such as energy losses, inefficient load forecasting, and poor voltage control. Smart grids use digital technology to enable real-time monitoring, optimize the generation and distribution process, and integrate renewable energy sources.

Olaniyi et al. (2024) argue that smart grids can significantly enhance grid stability by reducing transmission losses and improving the management of power flow. However, they also point out the high initial capital costs of smart grid deployment and the need for substantial investment in grid modernization. Additionally, Adewale et al. (2022) note that regulatory and policy frameworks in Nigeria need to evolve to support the integration of smart grid technologies, including establishing standards for data management, cybersecurity, and interoperability.

Privatization and its Impact on Service Delivery

The privatization of Nigeria's electricity sector, which occurred in 2013, has been the subject of significant debate. While the privatization was intended to improve efficiency, service delivery, and private sector involvement, the results have been mixed. Eze et al. (2023) provide a critical evaluation of the privatization process, concluding that its impact has been limited due to regulatory failures, lack of financial investment, and persistent operational inefficiencies. The authors highlight that despite the transfer of power assets to private companies, many privatized utilities still struggle to meet demand and provide reliable electricity services.

In a similar vein, Adebayo and Ogunyemi (2021) argue that privatization has not led to significant improvements in service quality due to weak regulatory oversight and political interference. Their study shows that while private operators have been able to make some improvements in operational performance, they still face significant financial and technical barriers. They emphasize that addressing these challenges will require stronger regulatory frameworks and greater private sector collaboration to ensure the long-term success of privatization.

Economic Impacts of Power Shortages

Several studies have investigated the broader economic implications of Nigeria's power shortages, especially within the industrial and commercial sectors. Adebayo and Ogunyemi (2021) show that power outages and an unreliable electricity supply have a direct negative impact on Nigeria's industrial sector, leading to higher production costs, decreased competitiveness, and lower investor confidence. Their research indicates that industrial businesses often resort to expensive backup generators to meet their energy needs, further exacerbating the cost of doing business in Nigeria. Additionally, Adebayo et al. (2023) explore how the country's energy poverty defined as the lack of access to reliable and modern energy services remains a significant obstacle to sustainable economic development. They argue that the failure to provide universal access to electricity not only affects industrial productivity but also hinders broader social development, including access to education, healthcare, and clean water.

Gaps in Existing Studies

While substantial research has been conducted on Nigeria's electrical power system, several critical gaps remain in the literature Despite growing interest in renewable energy, empirical studies on the technical and economic feasibility of integrating renewable energy into Nigeria's national grid are still sparse. Most research focuses on individual renewable sources like solar or wind, without addressing the combined potential of multiple renewable sources working in concert within the grid (Okafor & Chijioke, 2023). Although there is considerable interest in smart grid technologies, there is a lack of detailed empirical research on the practical implementation of these technologies in Nigeria. Specifically, there is a need to examine the challenges associated with smart grid adoption, such as cost barriers, infrastructure requirements, and the impact on grid stability (Olaniyi et al., 2024).

While technical and economic barriers have received significant attention, the political and institutional challenges that hinder the development of Nigeria's power sector are often underexplored. Research on how governance, corruption, and policy-making affect energy access and sector reforms is needed to better understand the root causes of inefficiencies in the system (Adewale et al., 2022). Another emerging area of research concerns the role of energy storage technologies, particularly battery storage, in stabilizing the grid and enabling the integration of intermittent renewable energy sources. Studies examining the feasibility and economic impact of energy storage systems in the Nigerian context are still limited (Eze et al., 2023). While the privatization of the Nigerian power sector has been widely discussed, there is a lack of longitudinal studies that evaluate its long-term impacts. Research that provides a detailed cost-benefit analysis of privatization, examining both service quality improvements and financial outcomes for power utilities, is needed to determine the success of this approach (Eze et al., 2023).

METHODOLOGY

This study adopts a descriptive and exploratory research design. The descriptive aspect is crucial for capturing the state of Nigeria's electrical power system by detailing its current inefficiencies, power shortages, and infrastructural challenges. The population of this study comprises a broad range of stakeholders who are directly or indirectly involved in Nigeria's electrical power system. Given the wide scope and heterogeneity of the study population, a combination of purposive sampling and stratified random sampling techniques is employed to ensure representativeness and depth of analysis. The study employed a mixed-methods approach, combing both quantitative and qualitative research instruments. Structured and semi-structured questionnaires are administered to policymakers, utility professionals, private sector actors, households, and industrial users. The use of Likert-scale items, multiple-choice questions, and open-ended responses enables both statistical analysis and contextual interpretation.

In-depth interviews are conducted with selected key stakeholders, including senior government officials, industry experts, and academics. The interview guide consists of open-ended questions designed to explore complex issues such as renewable energy integration, regulatory effectiveness, investment constraints, and the adoption of smart grid technologies. Interviews provide rich qualitative insights that complement survey findings. Document analysis is also employed as a key research instrument. Relevant policy documents, regulatory frameworks, sector performance reports, and official publications from institutions such as the Nigerian Electricity Regulatory Commission and the Nigerian Bulk Electricity Trading company are reviewed.

Primary data are collected through questionnaires, interviews, and focus group discussions conducted across selected urban and rural locations in Nigeria. While secondary data are obtained through an extensive review of academic literature, government publications, regulatory reports, and energy sector databases. These sources provide contextual and historical information that supports interpretation of primary data findings.

Quantitative data from questionnaires are analyzed using statistical software such as SPSS or Microsoft Excel. Descriptive statistics are used to summarize key variables, including electricity access levels, frequency of outages, consumption patterns, and user satisfaction. Inferential statistical techniques, such as chi-square tests and regression analysis, are applied to examine relationships between variables, including renewable energy adoption, grid modernization efforts, and service quality outcomes. Factor analysis was also employed to identify underlying factors influencing power system efficiency. Qualitative data obtained from interviews and focus group discussions are transcribed and analyzed using thematic analysis. This involves systematically coding responses to identify recurring themes and patterns related to energy access, renewable integration, smart grid deployment, privatization outcomes, and institutional challenges. Qualitative data analysis software such as NVivo or ATLAS.ti was also used to enhance accuracy and organization. To enhance the validity and reliability of findings, data triangulation is applied. This involves cross-checking results from surveys, interviews, focus groups, and document analysis to identify consistencies and discrepancies. By integrating multiple data sources and analytical methods, the study ensures a comprehensive and credible representation of the current state of Nigeria's electrical power system.

PRESENTATION AND ANALYSIS OF DATA

Research Question 1: Operational Inefficiencies and Infrastructural Challenges

Table I

Operational Challenge	Mean Score	Standard Deviation	Frequency (%)
Power Generation Inefficiencies	4.2	0.9	80%
Transmission Losses	4.6	0.8	85%
Distribution Network Instability	4.3	1.1	83%
Aging Infrastructure	4.0	0.9	77%
Lack of Maintenance and Investment	3.8	1.0	72%

Interpretation

Data from table 1 above shows that **transmission losses (**mean = 4.6) are the most significant issue facing the Nigerian power sector**. Power generation inefficiencies** are also seen as highly significant (mean = 4.2), particularly related to outdated plants and fuel inefficiencie**s. Distribution network instability** (mean = 4.3) indicates frequent issues with power delivery to end-users. **Aging infrastructure and lack of maintenance** are also serious issues but slightly less impactful compared to transmission problems.

Research Question 2: Integration of Renewable Energy and Its Impact on Sustainability, Reliability, and Cost-Effectiveness

Table 2

Impact Area	Mean Score	Standard Deviation	Frequency (%)
Renewable energy improves reliability	4.4	1.0	78%
Renewable energy improves sustainability	4.5	0.9	82%
Renewable energy reduces electricity costs	3.7	1.1	65%

Result from on table 2 above indicate that renewable energy improves reliability and sustainability with mean scores of 4.4 (frequency rate of 78%) and 4.5 (frequency rate of 82%). The table also shows that renewable energy also reduces electricity cost with a mean score of 3.7 (frequency rate of 65%). This by implication means that renewable energy can be integrated into power generation system in order to improve sustainability, reliability, and cost-effectiveness.

Hypothesis Testing

(Hi) Regression Analysis for Renewable Energy Integration

Table 3

Dependent Variable	Independent Variable	Coefficient (β_1)	p-value
Reliability	Renewable Energy Integration	0.48	< 0.01
Sustainability	Renewable Energy Integration	0.52	< 0.01

The positive coefficient of 0.48 for renewable energy integration suggests that for every increase in renewable energy (solar, wind, or hydro) integration into the grid, reliability improves. Since the p-value is less than 0.01, this relationship is statistically significant, meaning we can confidently conclude that renewable energy integration improves grid reliability. Similarly, the coefficient of 0.52 for sustainability shows a positive and statistically significant impact of renewable energy integration on the long-term sustainability of Nigeria's electricity supply. With the p-value being less than 0.01, we can infer that renewable energy plays a crucial role in enhancing the environmental and operational sustainability of the power sector.

DISCUSSION OF FINDINGS

This study sought to explore the operational inefficiencies and infrastructural challenges facing Nigeria's electricity generation, transmission, and distribution systems, as well as to assess the potential impact of renewable energy integration on the reliability and sustainability of the power grid. The findings reveal significant insights into both the challenges within the existing power infrastructure and the promising benefits of renewable energy integration.

The analysis of the operational inefficiencies and infrastructure challenges within Nigeria's power sector highlighted transmission losses, power generation inefficiencies, and distribution network instability as the most pressing issues. The mean scores for these inefficiencies were notably high, underscoring their critical impact on the overall performance of the power system. Transmission Losses (Mean = 4.6): Transmission losses were identified as the most significant challenge, with a mean score of 4.6. A large percentage of respondents rated this inefficiency as highly significant, reflecting the widespread recognition of the inefficiencies in Nigeria's transmission network. The high transmission losses are likely due to outdated transmission infrastructure, inadequate investment, and the lack of an efficient grid management system. These issues contribute to a large portion of the power generated being lost during transit, further exacerbating the already unreliable power supply. This inefficiency not only increases operational costs but also leads to frequent power outages and unreliable service, which significantly undermines the economic and social stability of the nation.

Power generation inefficiencies were the second most significant issue, with a mean score of 4.2. Respondents particularly emphasized the age and operational inefficiency of power plants, the reliance on high-cost and polluting fossil fuels, and the lack of regular maintenance. These inefficiencies contribute to the low overall capacity of Nigeria's power sector and the high cost of electricity generation. Outdated plants also require extensive maintenance and face frequent breakdowns, which further limit the supply of electricity to the population. As such, this inefficiency exacerbates the nation's energy deficit, rendering power supply less dependable and often insufficient for both industrial and household needs. Distribution Network Instability (Mean = 4.3) are The instability in the distribution network was also a critical issue, with a mean score of 4.3. This refers to the frequent and prolonged power outages that consumers, both households and industries, experience. The instability can be attributed to a combination of poor infrastructure, lack of investment, and ineffective management of the distribution network. Distribution network issues severely affect the reliability and accessibility of power to end-users, resulting in a diminished quality of life for households and hampering industrial productivity. Inadequate grid stability also undermines the confidence of both consumers and investors in the power sector, hindering any potential for further development and improvement. Aging Infrastructure (Mean = 4.0) and Lack of Maintenance (Mean = 3.8) are aging infrastructure and inadequate maintenance were also significant challenges, they were viewed as slightly less critical than transmission and power generation issues. The

mean score for aging infrastructure was 4.0, indicating a recognition that outdated infrastructure remains a major barrier to improving Nigeria's electricity system. Inadequate maintenance and insufficient investment were similarly viewed as serious challenges (mean = 3.8). The lack of timely repairs and upgrades to infrastructure, combined with underinvestment in the power sector, contributes to the exacerbation of other operational inefficiencies. This situation has created a vicious cycle where the failure to invest in new technologies or improvements in the system leads to higher operational costs and even more frequent outages.

The second aspect of the study examined the potential impact of integrating renewable energy sources (solar, wind, and hydro) into Nigeria's electricity grid. The results of the regression analysis suggest that renewable energy integration plays a positive and significant role in improving both the reliability and sustainability of the power system. Reliability ($\beta_1 = 0.48$, $p < 0.01$): The regression model indicated a positive and statistically significant relationship between renewable energy integration and reliability. The coefficient of 0.48 suggests that an increase in renewable energy capacity (such as solar, wind, or hydro) is associated with an improvement in grid reliability. This relationship is statistically significant (p-value < 0.01), providing robust evidence that renewable energy integration can reduce power outages and improve the stability of the electricity supply. By diversifying the energy mix and reducing reliance on fossil fuels, renewable energy sources can offer a more reliable and sustainable power supply, mitigating some of the risks associated with traditional power generation methods. Similarly, the integration of renewable energy sources was shown to have a positive impact on the long-term sustainability of Nigeria's electricity system. With a coefficient of 0.52, renewable energy integration is linked to a more sustainable power grid, contributing to environmental sustainability by reducing carbon emissions and increasing the efficiency of energy generation. The statistical significance of this relationship (p-value < 0.01) suggests that renewable energy not only helps in addressing the immediate challenges of power supply but also provides a pathway toward a more sustainable energy future. The move towards cleaner and more efficient sources of energy can greatly reduce the country's dependence on fossil fuels, improving energy security and helping to mitigate the effects of climate change.

SUMMARY OF FINDINGS

This study focused on two major issues in Nigeria's electricity sector: the operational inefficiencies and infrastructural challenges in the generation, transmission, and distribution systems, as well as the potential role of renewable energy in improving the reliability, sustainability, and cost-effectiveness of the power grid.

1. The findings reveal that the most pressing issues within Nigeria's power sector are Transmission losses were rated as the most significant operational inefficiency. A mean score of 4.6 indicates that respondents viewed transmission inefficiencies stemming from outdated infrastructure, poor grid management, and inadequate investments as a key obstacle to reliable power supply. The high transmission losses lead to power supply disruptions, contributing to the overall unreliability of the grid. The consequences of this are particularly severe in rural areas where power outages are frequent and prolonged. Improving transmission infrastructure and reducing transmission losses are crucial steps for enhancing grid reliability. Power generation inefficiencies were also identified as a significant challenge. The inefficiencies are largely attributed to outdated power plants, the high operational costs of fuel (especially due to the reliance on expensive diesel and gas for generation), and poor maintenance practices. A mean score of 4.2 reflects the high degree of concern stakeholders have about the insufficient power generation capacity in Nigeria, which leads to electricity shortages and load shedding. These inefficiencies have a direct impact on the overall energy availability in the country and emphasize the urgent need for the modernization of existing plants and investment in new, more efficient generation technologies. Distribution network instability is another critical issue, with a mean score of 4.3. Problems such as grid instability, high distribution losses, and poor infrastructure contribute to a lack of reliable power delivery to end-users. The study highlights the frequent outages and grid failures, especially in

urban and semi-urban areas, as a direct consequence of these issues. It is clear that addressing these challenges would not only stabilize power supply but also improve the quality of service for consumers. Distribution infrastructure improvements, such as expanding the grid and enhancing the management systems, are necessary for reducing outages and improving power delivery. While aging infrastructure and lack of maintenance were also rated as significant challenges, they were slightly less critical than transmission and generation issues. With mean scores of 4.0 and 3.8 respectively, respondents highlighted that the country's power infrastructure has deteriorated over time due to insufficient investment and long-term planning. The lack of regular maintenance further exacerbates the inefficiencies, causing increased downtime and service interruptions. While not as urgent as transmission losses or generation inefficiencies, these factors still need attention to prevent further deterioration of the grid and ensure the long-term sustainability of the power sector.

2. The study also assessed how the integration of renewable energy sources such as solar, wind, and hydro can improve the reliability and sustainability of Nigeria's electricity grid. The regression analysis revealed that the integration of renewable energy sources significantly improves the reliability of the power grid. The positive coefficient of 0.48 and the statistically significant p-value of less than 0.01 suggest that increasing renewable energy integration can help reduce power outages and improve grid stability. By diversifying the energy mix, renewable energy can decrease the dependence on fossil fuels, which are often subject to supply disruptions and price volatility. This diversification of energy sources can make the grid more resilient to external shocks, improving the overall stability and reliability of the electricity supply. Similarly, renewable energy integration was found to have a positive and statistically significant impact on the sustainability of the electricity supply. With a coefficient of 0.52 and a p-value less than 0.01, the study suggests that renewable energy plays a crucial role in enhancing the long-term sustainability of Nigeria's power sector. By reducing the reliance on fossil fuels and decreasing carbon emissions, renewable energy sources like solar, wind, and hydro can contribute to more sustainable electricity generation. Moreover, renewable energy can help improve energy security by providing more decentralized and locally available sources of power, which are less vulnerable to external disruptions, such as fuel shortages or price fluctuations.

CONCLUSION

In conclusion, the study provides a comprehensive overview of the operational inefficiencies and infrastructural challenges within Nigeria's electrical power system, offering valuable insights into the key issues that need addressing. The primary operational inefficiencies transmission losses, power generation inefficiencies, and distribution instability are deeply rooted in outdated infrastructure, insufficient maintenance, and poor management practices. These inefficiencies contribute significantly to the nation's persistent power shortages, high operational costs, and unreliable electricity supply.

On the other hand, the study highlights the significant role that renewable energy integration can play in improving the Nigerian power sector. By diversifying the energy mix and reducing reliance on fossil fuels, renewable energy sources like solar, wind, and hydro can enhance the sustainability, reliability, and cost-effectiveness of electricity supply. The findings indicate that integrating renewable energy will not only improve the reliability and stability of the grid but also contribute to long-term environmental sustainability by reducing carbon emissions and mitigating the impacts of climate change. This study reinforces the need for substantial investments in infrastructure upgrades, especially in transmission and distribution networks, and emphasizes the importance of incorporating renewable energy sources into the national energy strategy to achieve a more sustainable and reliable power system.

RECOMMENDATIONS

Based on the findings of this study, the following recommendations are made to improve Nigeria's electricity generation, transmission, and distribution systems

1. Immediate attention should be given to modernizing Nigeria's transmission and distribution networks. This includes upgrading old transmission lines, improving grid management technologies, and increasing investments in infrastructure to reduce transmission losses and improve reliability. Effective solutions like smart grid technologies and decentralized power distribution should also be explored.
2. Nigeria's power generation capacity needs urgent expansion and modernization. Investment should be directed toward upgrading aging power plants, replacing outdated equipment, and improving the efficiency of fuel usage. Additionally, promoting the use of cleaner technologies such as combined-cycle power plants could help reduce operational inefficiencies and environmental impact.
3. Policymakers should implement stronger incentives for the development of renewable energy projects, including solar, wind, and hydro. This can include tax incentives, feed-in tariffs, and subsidies to encourage private investment in renewable energy infrastructure. Furthermore, the government should streamline regulatory frameworks to facilitate the faster deployment of renewable energy technologies.
4. There is a need for more government support in research and development (R&D) to explore new renewable energy technologies that can be deployed effectively in Nigeria's diverse geographic and climatic regions. Collaborative efforts between government, academia, and the private sector can drive innovation and make renewable energy more viable and cost-effective.
5. To ensure the effective implementation of renewable energy solutions and the modernization of existing infrastructure, it is crucial to invest in capacity building and training programs. These programs should target utility staff, engineers, and policymakers to equip them with the skills needed to manage new technologies, including smart grids and renewable energy integration.
6. A national strategy for ensuring consistent maintenance of power infrastructure should be developed. Long-term planning is crucial to avoid the neglect of power generation and distribution assets. The government and utility companies must ensure that adequate funding is allocated to maintenance efforts, as well as to the development of new infrastructure.
7. Public awareness campaigns should be launched to educate both the public and industrial users about the benefits of renewable energy integration. Additionally, ongoing engagement with key stakeholders including local communities, utility providers, and industry experts should be maintained to align the energy transition with the needs and expectations of end-users.

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