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NIGERIA'S ELECTRICITY TRANSITION: A SYSTEMATIC ANALYSIS OF INFRASTRUCTURE, TECHNOLOGY, AND GOVERNANCE PATHWAYS

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Abstract: Reliable electricity is vital for Nigeria's economic growth and social welfare, yet chronic outages and supply shortfalls leave nearly 90 million citizens without power, undermining progress toward SDG 7. Despite the 2013 privatization, the grid continues to experience frequent collapses, over 30% transmission losses, and only 55% electrification. In this study, we analyze pre– and post–privatization performance data, simulate scenarios that tap Nigeria's 427 GW solar and wind potential, and assess smart–grid solutions for real–time monitoring and demand management. We find that diversifying the energy mix with decentralized solar power and storage, deploying predictive maintenance meters, and strategically expanding network capacity can reduce losses by up to 20% and alleviate grid congestion in both urban and rural areas. Our contributions include a data–driven diagnosis of systemic inefficiencies, an integrated design framework for distributed renewables and digital controls, and targeted policy recommendations that align investments with climate objectives. We urge policymakers, utilities, and investors to adopt these strategies—combining decentralized clean energy, grid digitization, and critical infrastructure upgrades—to ensure a resilient, efficient, and universally accessible power system for all Nigerians
Keywords: Nigeria Electricity Grid; National Grid Collapse; Energy Security; Electricity Supply; Renewable Energy

1. INTRODUCTION

Energy, fundamentally defined as the ability to do work, has been a central component in the advancement of modern civilization. The advent of electricity has revolutionized various aspects of human life, transforming the way people live, work, and interact. The development and utilization of electricity (electrical energy) represent a significant milestone in humanity's ability to convert energy from one form to another for practical use. This transformative effort has enabled vast improvements in various sectors, including lighting, one of the initial drivers behind the quest for electrical power. Moreover, electricity has become a crucial driver of economic growth, powering industries and enabling the development of modern technologies. Nigeria, the most populous country in Africa, has experienced substantial population growth, increasing from 203.3 million in 2019 to 213.4 million in 2021, with the current estimate at 227 million. This rapid population growth has led to a surge in electricity demand, underscoring the need for reliable and efficient power. With this population growth, electricity demand has also surged correspondingly. The increasing demand for electricity has put pressure on the existing power infrastructure, highlighting the need for investments in power generation, transmission, and distribution.

The historical pursuit of electric lighting in Nigeria began in Lagos during the British colonial era in the late 1890s and early 1900s. The initial focus was on providing electricity to urban areas, with the first power plant commissioned in 1886. The primary considerations at that time were the cost-efficiency of electricity production and the affordability for consumers (O. A. Lawal et al., 2024). Electricity generation in Nigeria commenced in Lagos in 1886 with the deployment of generators capable of producing 60 kW. Following the amalgamation of the Northern and Southern protectorates in 1914, which formed modern Nigeria, other towns independently developed their electric power supply systems. This decentralized approach laid the groundwork for the country's energy infrastructure and highlighted early efforts to address the growing demand for reliable electricity (Awosope, n.d.). Expanding electricity services to other major cities marked a significant milestone in Nigeria's energy development. The following major cities received a dose of electricity supply in the following order: Port Harcourt (1928), Kaduna (1929), Enugu (1933), Maiduguri (1934), Yola (1937), Zaria (1938), Warri (1939), and Calabar (1939) (Awosope, n.d.). Since then, Nigeria's electricity power system has undergone numerous changes in its physical

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structure and organization. The Nigerian government has implemented various reforms to improve the efficiency and reliability of the power sector. The merging of the Niger Dam Authority and the Electricity Corporation of Nigeria (ECN) (*The Nigeria Electricity System Operator*, n.d.). By 1999 – 2005 (the advent of democratic government), an act was enacted establishing PHCN, an Initial Holding Company (IHC), because of the Government's effort to revitalize the power sector. They separated generations from the grid, leaving an independent network to enter government and private generation contracts. Nigeria permitted government and private power generation activities, promoting power generation and distribution across its 36 states.

The Electric Power Sector Reform Act of 2005 was a landmark legislation that paved the way for the privatization of the power sector. This intervention began when significant problems in the Nigerian electricity sector, primarily related to power outages and unreliable services, compelled the Nigerian government to take radical measures (*Nigeria's Electricity Sector Reform and Unbundling; Good or Bad? – Renewable Energy Technology Training Institute*, n.d.). It then enacted the Electric Power Sector Reform Act of 2005, which provided for the vertical separation of the Nigerian Electric Power Authority along the generation, transmission distribution, and retail functional lines and the incorporation of the various business segments as successor companies, as well as a method of asset transfer, liabilities, and personnel to these successor companies, which are subsequently privatized (*Nigeria Power Sector Reform; Good or Bad?*, n.d.). The Nigerian National Power Utility Company was unbundled into 18 successor companies: 6 generation companies, 12 distribution companies covering all 36 Nigerian states, and one national power transmission company created from the defunct NEPA.

Subsequently, between November 2013 and November 2014, the privatization of all the generation and distribution companies was completed, while the government retained ownership of the transmission company (*Nigeria's Electricity Sector Reform and Unbundling; Good or Bad? – Renewable Energy Technology Training Institute*, n.d.). On 30 September 2013, following the privatization process initiated by Goodluck Jonathan's regime, PHCN (Power Holding Company of Nigeria) ceased to exist. As provided in the Electric Power Sector Reform Act of 2005, the independent regulatory agency was tasked with monitoring and regulating the Nigerian electricity industry, issuing licenses to market participants, and ensuring compliance with market rules and operating guidelines (*Nigeria's Electricity Sector Reform and Unbundling; Good or Bad? – Renewable Energy Technology Training Institute*, n.d.). Despite these reforms, the Nigerian power sector continues to face significant challenges, including frequent power outages and grid collapses. One of the most pressing issues confronting the industry is the frequency of national grid collapses, which have posed significant disruptions to the country's electricity supply. These grid collapses, often attributed to technical deficiencies, inadequate maintenance, and system instability, have underscored the urgent need for comprehensive reforms and investment in the power infrastructure (Ohunakin et al., 2014). As Nigeria continues its quest for sustainable energy development and economic growth, addressing the underlying causes of grid collapses and advancing power sector privatization remain paramount.

This paper reviews the national grid's performance before and after privatization, analyzing the root causes, frequency, and response times of grid collapses. It examines the efficacy of privatization measures and explores strategies for overcoming challenges, such as inadequate supply and unreliable service. This study provides a roadmap for enhancing Nigeria's power sector's resilience, reliability, and sustainability by integrating renewable energy resources and implementing advanced technological solutions.

2. NIGERIA'S ELECTRICITY GRID: AN OVERVIEW

Nigeria's electricity grid is a complex network of power generation, transmission, and distribution systems that play a crucial role in the country's economic development. The grid's performance has a direct impact on the overall economy, as well as the daily lives of Nigerians. With over 200 million people, Nigeria's electricity demand is increasing rapidly, driven by urbanization, industrialization, and economic growth. The Nigerian electricity grid faces significant challenges, including inadequate power generation, transmission losses, and inefficient distribution systems. Frequent power outages, voltage fluctuations, and grid collapse compromise the grid's reliability and efficiency. These challenges have resulted in a significant gap between electricity demand and supply, with many Nigerians relying on alternative energy sources, such as generators and solar power.

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Despite these reforms, the Nigerian power sector continues to face significant challenges, including inadequate power generation, transmission losses, and inefficient distribution systems. The industry requires substantial investments in power generation, transmission, and distribution infrastructure to meet the growing demand for electricity. Developing renewable energy sources, such as solar and wind power, also offers significant opportunities for Nigeria to diversify its energy mix and reduce its reliance on fossil fuels.

With the above, the contributions of this study are to:

- Comprehensive Grid Performance Diagnostics: We conduct a multidimensional assessment of Nigeria's transmission and distribution networks, using power-flow simulations, stability indices, and loss decomposition to quantify bottlenecks, voltage deviations, and frequency excursions under varying demand scenarios.
- Optimized Reliability Enhancement Strategies: By integrating mixed-integer linear programming (MILP) models for renewable portfolio selection with distribution network reinforcement algorithms, we prescribe targeted upgrades, such as advanced metering infrastructure (AMI), distribution management systems (DMS), and dynamic line rating implementation, to minimize technical losses and maximize system resilience.

Advanced Energy Management Framework: We develop a GIS-enabled planning tool that couples demand-side management (DSM) strategies, predictive maintenance schedules, and cost-benefit analyses to produce actionable investment roadmaps. These blueprints guide utilities and policymakers in priority deployments of generation assets, grid hardening measures, and efficiency retrofits to drive economic and environmental sustainability.

3. BACKGROUND: Nigeria's National Power Grid (NNPG)

A power grid is a network of high-power lines and associated equipment used to transmit and distribute electricity over a geographic area (O. A. Lawal, 2023). Nigeria's national power grid is a critical component of its energy infrastructure, playing a vital role in meeting the electricity needs of its growing population, which is projected to reach 400 million by 2050. Nigeria's national power grid connects power generation stations to electrical loads throughout the country. The grid's extensive network spans the country, covering a vast geographic area of over 923,768 square kilometers and supplying electricity to millions of households, businesses, and industries, the backbone of the country's economy. The power grid comprises twenty-seven operational grid-connected generators fueled by a combination of thermal and hydroelectric power sources. The transmission system comprises high-voltage transmission lines, substations, and transmission towers that collaborate to transmit electricity from power generation sources to the distribution systems over long distances, thereby minimizing energy losses. The transmission system comprises high-voltage transmission lines, substations, and towers that transmit electricity from power generation sources to the distribution systems. It is designed to operate within certain limits, stability limits, in line with voltage, current, and frequency, which is a critical indicator of the balance between electricity supply and demand. These stability limits are crucial for ensuring the reliable operation of the grid, as deviations from these limits can lead to grid instability and potentially result in collapse. The national grid's stabilization and maintenance are achieved through grid frequency control, where power system operators closely monitor the system frequency, which indicates the balance between supply and demand.

For voltage control, power system operators utilize voltage control devices, such as transformers, capacitors, and voltage regulators, to regulate and stabilize voltage levels. These devices are adjusted in real-time to ensure that voltage remains within acceptable limits, preventing voltage fluctuations that could disrupt the grid's stability (*How Do Power System Operators Maintain the Stability of the Grid? | ResearchGate*, n.d.). From Figure 1, over the last 13 years, the NNPG has collapsed at least 225 times. This alarming frequency of grid collapses highlights the need for urgent attention to address the underlying causes of these collapses and implement measures to improve the grid's resilience and reliability, such as upgrading the grid's infrastructure, improving the efficiency of power generation and transmission, and enhancing the grid's ability to respond to disturbances and faults. The consequences of grid collapses can be severe, including power outages, equipment damage, and economic losses, which can significantly impact the country's economy and the well-being of citizens.

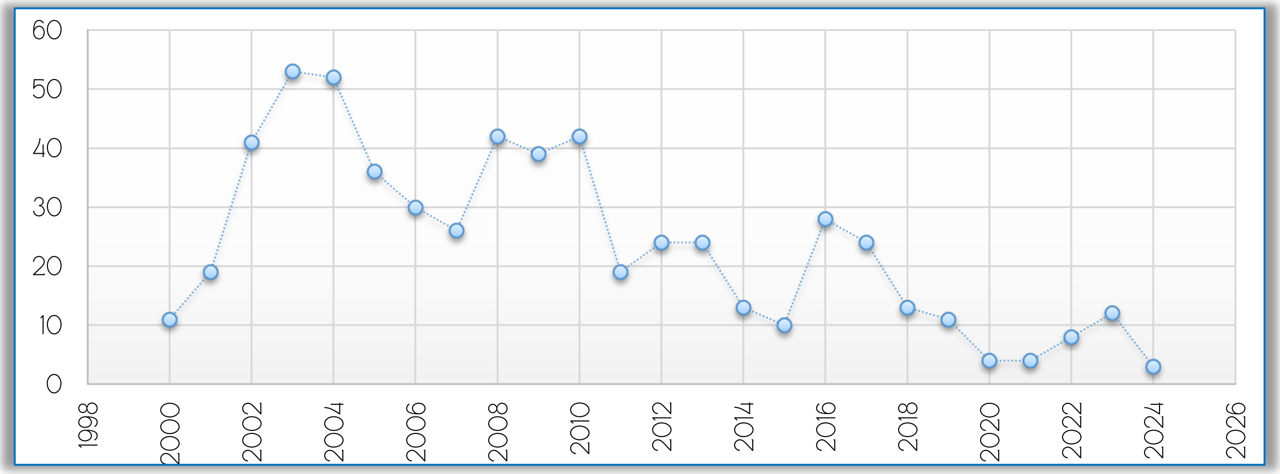

Figure 1. National grid collapses from 2000 to 2024 (Jimoh & Raji, n.d.)

4. CURRENT SITUATION OF THE NIGERIA ELECTRICITY GRID SYSTEM

A critical review of the current state of the generation system, transmission system, and distribution system, as well as the capacity and challenges in each section of the power sector, is presented below. This review highlights the frequent collapse of Nigeria's electricity power grid, alongside concerns about future reliability and resilience in the industry.

Nigeria's Generation System (NGS)

Electricity in Nigeria is generated through thermal and hydropower sources. The country's electricity generation mix is dominated by fossil fuels, particularly natural gas, which accounts for approximately 86% of the installed capacity, while hydropower sources account for the remaining 14% (Oniemola, 2016). The primary source of electricity generation in Nigeria is fossil fuels, particularly natural gas, which is abundant in the country. The reliance on fossil fuels for electricity generation has significant implications for the country's energy security, environmental sustainability, and economic development. The generation system is a critical phase of the power network chain in Nigeria, generating electricity at a medium voltage level of 10.5- 16 kV, which is then transmitted to the national grid at a primary transmission voltage of 330 kV (Ayamolowo et al., 2019). The transmission voltage is critical in ensuring efficient electricity transmission over long distances, minimizing energy losses, and maintaining grid stability.

Nigeria has twenty-seven (27) power-generating plants connected to the national grid that can generate 11,165.4 MW of electricity (*Nigeria Power Sector Reform; Good or Bad?*, n.d.). These power-generating plants are strategically located across the country, with the majority being thermal power plants, while a few are hydroelectric power plants. The plants are managed by generation companies (GenCos), independent power providers, and the Niger Delta Holding Company. Managing these power-generating plants is critical in ensuring reliable and efficient electricity generation, transmission, and distribution. The generation system in Nigeria faces several challenges, including inadequate generation capacity, inefficient generation technologies, and insufficient maintenance of generation infrastructure. These challenges have resulted in frequent power outages, voltage fluctuations, and grid instability. To address these challenges, significant investments are needed in generation capacity expansion, technology upgrades, and infrastructure maintenance. Additionally, there is a need for a diversified

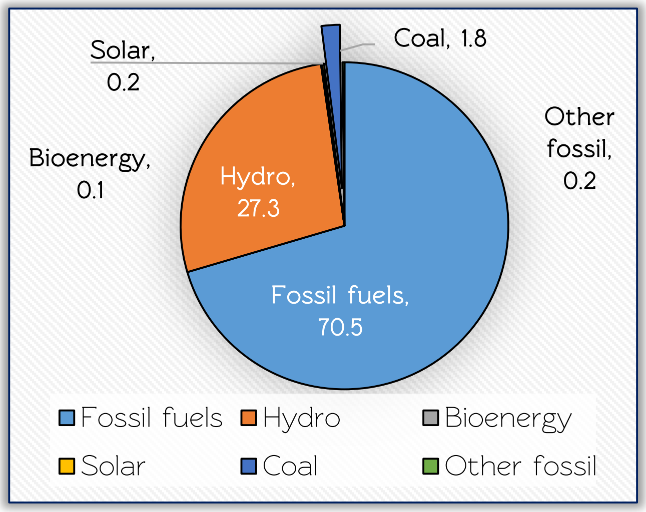

Figure 2. Electricity Generation Mix in Nigeria

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energy mix, with a greater emphasis on renewable energy sources, such as solar and wind power, to reduce the country's reliance on fossil fuels and mitigate the impact of climate change.

Figure 2 depicts the low ratio of solar energy compared to other sources. The future of Nigeria's generation system depends on its ability to adapt to changing energy demand, technological advancements, and environmental sustainability requirements. There is a need for a comprehensive energy policy framework that prioritizes energy security, environmental sustainability, and economic development. This framework should promote investments in renewable energy sources, energy efficiency measures, and grid modernization.

Challenges in NGS Contributing to the Frequent National Grid Collapse

Three main factors typically influence the productivity and performance of Generation companies (GenCos) in Nigeria. These include energy sources, finance, and the activities of the other segments of Nigeria's electricity supply industry (NESI) value chain. Ensuring the availability, reliability, sustainability, and affordability of energy sources is crucial for achieving and maintaining higher and sustained power generation in the country. It requires a coordinated effort from all stakeholders, including government, investors, and industry players (A. Lawal et al., 2017). Currently, NESI has undiversified energy sources, with GenCos being heavily dependent on thermal energy (80% of energy sources) and hydroelectric power (20%). The lack of diversification in energy sources makes the sector vulnerable to fluctuations in the global market. It limits the country's ability to reduce its reliance on fossil fuels and transition to cleaner energy sources. The government and investors have not explored diversifying energy sources due to the relative affordability of large hydroelectric and gas-powered plants compared to alternative sources. However, this approach neglects the long-term benefits of diversifying the energy mix, including reduced greenhouse gas emissions, improved energy security, and enhanced economic competitiveness.

Unfortunately, despite efforts to address them, challenges persist in Nigeria's generation system, significantly impacting its ability to meet growing demand. One of the most pressing challenges in this sector is the insufficient generation capacity, resulting in a significant gap between electricity supply and demand. Nigeria's power generation capacity is inadequate to meet the growing demand. Despite efforts to increase capacity, such as the National Integrated Power Project (NIPP) launched in 2005, generation remains below the required level, and the country continues to rely heavily on backup generators, which are expensive and polluting. After privatization in 2013, the government unbundled the Power Holding Company of Nigeria (PHCN) and sold off generation and distribution assets to private investors. While privatization was intended to attract investment and improve efficiency, the generation capacity has not increased significantly due to challenges such as funding constraints, regulatory uncertainty, and the slow implementation of reforms. For instance, in 2020, Nigeria's peak electricity generation was around 5,420 megawatts (MW), far below the estimated peak demand of over 25,000 MW (*Development Projects*, n.d.). This significant gap between supply and demand has led to frequent power outages, voltage fluctuations, and grid instability, severely impacting the economy, industry, and households.

Another critical challenge is the poor maintenance culture. It has become evident that Nigeria's power generation infrastructure suffers from inadequate maintenance, resulting in frequent breakdowns and outages that further exacerbate the already insufficient generation capacity. Under state ownership, maintenance practices were deficient due to limited funding and expertise, resulting in frequent breakdowns and outages. Although privatization aimed to improve maintenance through increased private sector involvement, challenges such as inadequate funding, a lack of skilled personnel, and corruption in the contract awarding process hindered significant improvements. Fuel supply challenges also plague the sector, as most of Nigeria's power generation relies on gas-fired plants. The country faces challenges in its gas supply, resulting from pipeline vandalism and fluctuations in gas prices, even after privatization. For instance, in 2016, attacks on gas pipelines by militants in the Niger Delta region disrupted gas supply to power plants, resulting in a significant drop in generation capacity (Nigeria Militants Blow up Gas, Oil Pipelines. Another incident recorded was on 11 December 2023 between 13:48hrs & 13:49hrs, there was a simultaneous tripping of four (4) 330kV circuits (Olorunsogo/Ikeja West, Osogbo/Ihovbor, Osogbo/Ikeja West, and Afam/Alaoji). This resulted in the loss of 878.13 MW due to the separation of Egbin, Olorunsogo Phase I & II, and Paras power plants, located on the western axis of the grid. As a result, the grid frequency dropped from 50.25 Hz to 48.01 Hz, which led to the cascaded tripping of several thermal and hydropower plants and ultimately caused the grid to collapse. Two

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potential remote causes were identified. Firstly, the multiple tripping of interconnected 330kV circuits is suspected to result from relay maloperation or poor coordination. Secondly, the simultaneous tripping of Egbin, Olorunsogo I & 2, and Paras power plants would have resulted from a disruption in gas supply via the western axis of the ELPS gas pipeline (*2023_Q4_Report_Final-1.Pdf*, n.d.). These incidents underscore the grid's vulnerability to disruptions and the need for urgent attention to address the underlying causes of these collapses, as well as to implement measures that enhance the grid's resilience and reliability.

Additionally, transmission constraints hinder the distribution of generated power to consumers. Even when power is generated, transmission constraints hinder its distribution to consumers, resulting in a significant portion of generated electricity being lost during transmission. If GenCos were to improve their operational capacity, these improvements would not be accommodated because the transmission network suffers from an aging infrastructure, inadequate investment, and technical losses. The transmission network is a critical component of the power sector, and its inefficiencies have a ripple effect on the entire industry, resulting in reduced electricity supply, increased power outages, and decreased economic productivity. In 2021, the Nigerian Electricity Regulatory Commission (NERC) reported that transmission constraints accounted for over 50% of power outages in the country (*NIGERIAN ELECTRICITY REGULATORY COMMISSION*, n.d.). This highlights the need for urgent investment in the transmission network, including the upgrading of existing infrastructure, expansion of transmission capacity, and the adoption of new technologies to enhance transmission efficiency. Section IV provides more details.

Ultimately, inconsistent policies and inadequate regulatory frameworks hinder investment and impede the development of reliable power generation infrastructure. The lack of a stable policy framework and effective regulatory oversight creates uncertainty for investors, discourages long-term investments in the sector, and hinders the development of a competitive and efficient electricity market. For example, frequent changes in government policies and regulations create uncertainty for investors, discouraging long-term investments in the sector (*Sustainability | Free Full-Text | Economic Policy Uncertainty and Firm Value: Impact of Investment Sentiments in Energy and Petroleum*, n.d.). The government and regulatory agencies must collaborate to create a stable and enabling environment for investment in the power sector, including the development of a comprehensive energy policy framework, the establishment of a strong and independent regulatory agency, and the promotion of transparency and accountability within the industry. After privatization, there has been frequent political interference, inadequate enforcement mechanisms, and a lack of coordination among regulatory agencies. These challenges must be addressed through establishing a strong and independent regulatory agency, developing effective enforcement mechanisms, and promoting coordination and cooperation among regulatory agencies.

Nigeria's Transmission System (NTS)

Like Nigeria's Generation System (NGS), the Transmission System was primarily controlled by the state-owned utility, the National Electric Power Authority (NEPA). During the 1960s, Nigeria's power transmission system was characterized by the interconnection of power stations, including Kainji, Jebba, Shiroro, Afam, Delta (Ughelli), Sapele (Ogorode), and Egbin (Lagos). However, the transmission infrastructure during this period was largely inadequate and outdated, with significant portions of the network suffering from underinvestment and neglect, resulting in frequent breakdowns and inefficiencies. Maintenance practices were often subpar, leading to further deterioration of the transmission system. The lack of modernization and expansion projects resulted in an insufficient transmission capacity to meet the growing electricity demand nationwide, leading to a significant gap between electricity supply and demand (A. Lawal et al., 2017). Moreover, the regulatory environment was characterized by inefficiency and bureaucracy, further hindering the development of the transmission sector and creating an unfavourable business environment for investment and growth (O. A. Lawal, 2021; *Nigeria - Power Sector Recovery Operation*, n.d.).

The unbundling of the Power Holding Company of Nigeria (PHCN) resulted in the creation of the Transmission Company of Nigeria (TCN). TCN was incorporated in November 2005 and operates in three central departments: Transmission Service Provider (TSP), Market Operators (MO), and System Operators (SO). The TSP oversees the maintenance of cables and towers that transmit bulk power from generators to distribution companies. The MO handles market processes, rules, enforcement, finances, and other related activities. The SO maintains, coordinates, and stabilizes the national power grid. Independent bodies such as the Nigerian Electricity Regulatory Commission (NERC) and the Rural Electrification Agency (REA) were also established to monitor progress, maintain transparency, and ensure compliance with regulatory requirements. The state-controlled TCN links the Generation Companies (GenCos) and Distribution Companies (DisCos). As the only government-owned entity in the power value chain, TCN plays a critical role in ensuring the reliable transmission of electricity from generation sources to distribution networks. Currently, TCN has transmission capabilities of approximately 6 GW, with an infrastructure comprising around 6,680 km of 330 kV lines, 7,780 km of 132 kV lines, and 24,000 km of sub-transmission lines (33 kV) [13]. The transmission infrastructure also includes 330/132 kV substations with an installed transformation capacity of 10,166 MVA and 132/33/11 kV substations with an installed transformation capacity of 11,660 MVA [20]. These transmission assets play a crucial role in ensuring the reliable and efficient transmission of electricity nationwide and require regular maintenance and upgrades to maintain optimal performance. (*Nigerian Electricity Transmission Grid - Issues and Way Forward, By Odion Omonfoman - Premium Times Opinion*, n.d.).

Challenges in NTS Contributing to the Frequent National Grid Collapse

Privatization aimed to attract private investment, improve efficiency, and modernize the transmission network to address the challenges faced during the pre-privatization era. However, despite privatization, the transmission system continues to face significant challenges, including inadequate infrastructure, vandalism, and operational inefficiencies. The installed generation capacity is approximately 12,500 MW, and the available capacity is 7,000 MW, resulting in a net capacity of about 5,500 MW. This significant gap between installed and available capacity underscores the need for urgent investment in expanding generation capacity infrastructure. Meanwhile, figures from the Federal Ministry of Power indicate a national peak demand estimate of 19,100 MW, 68% higher than the current transmission capacity and 5,500 MW of distribution network operational capability. This demand-supply gap has led to frequent power outages, voltage fluctuations, and grid instability, severely impacting the economy, industry, and households.

There were plans to achieve 10,000 MW of national grid transmission by the end of 2023; however, the increasing attacks and vandalism of electricity transmission towers across the country threatened to undermine these efforts. The growing incidence of vandalism and sabotage has exacerbated the challenges faced by the transmission system, resulting in frequent grid collapses and power outages. According to daily lives, one of the most far-reaching incidents in a negative sense was the 8 April 2022 incident, which happened around 6:30 pm, literally plunging the national power grid to a very low level, causing a system collapse. This incident highlights the vulnerability of the transmission system to disruptions and the need for urgent attention to address the underlying causes of these collapses and implement measures to improve the grid's resilience and reliability. Days later, officials of the TCN noted that they had found transmission tower number 104 at Oku Iboku in Akwa Ibom State, along the 330 kilovolt (kV) Ikot Ekpene to Odukpani transmission line, to have been vandalized and had indeed fallen due to the impact. The impact of this incident was severe, resulting in a significant disruption to the electricity supply and highlighting the need for improved security measures to protect transmission infrastructure.

It took a while for the reconstruction work on the vandalized transmission to be completed, while work to fortify other minimally vandalized towers along the same route was carried out to enable the restringing and tensioning of the 330kV DC transmission line before it was energized. Completing these reconstruction works was critical in restoring the electricity supply and ensuring the reliable operation of the transmission system. Additionally, such an incident occurred in Ogun State, where three transmission towers on the 132 kV Papalanto/Ojere double-circuit transmission line recently collapsed after being vandalized, resulting in power outages around Abeokuta and its environs (*2023_Q4_Report_Final-1.Pdf*, n.d.). All these acts of vandalism have contributed to the frequent blackouts experienced. The increasing incidence of vandalism and sabotage has significantly disrupted the electricity supply, underscoring the need for enhanced security measures to safeguard transmission infrastructure. The study, "The Insight and Foresight of the Nigerian Power Transmission System: An Overview" (n.d.), revealed that 7% of the generated power is lost during the transmission process. These significant losses across the value chain can be linked to technology limitations and outdated transmission infrastructure, resulting in reduced electricity supply and decreased economic productivity. These losses are exacerbated in rural

areas because of the irregular maintenance of older infrastructure. The lack of regular maintenance and upgrading of transmission infrastructure has reduced transmission efficiency, increased energy losses, and decreased reliability.
Other challenges identified by GenCos were instability and the unavailability of most transmission lines, which contributed to the grid collapse. It's worth mentioning that the frequent political interference by the government in Manitoba Hydro International (MHI) was a serious challenge that impeded the goal of restructuring the TCN to international best practices. Other challenges affecting Nigeria's transmission system include, but are not limited to, the inability to carry out real-time operations, TCN radial lines; most TCN lines are radial, not double circuit, thereby limiting the redundancy in the system, which increases system instability, ineffective system reliability management, and issues relating to communities. In addition, inadequate and outdated infrastructure to meet demands, a transmission and distribution network manned by insufficient engineers and technicians, poor communication, and coordination of activities between TCN and distribution companies (DisCos) have contributed significantly to the country's frequent national power grid collapses over time.

Nigeria's Distribution System (NDS)

Nigeria's distribution system plays a crucial role in the country's power sector, responsible for delivering electricity from the transmission network to end-users across various sectors of the economy. The distribution system is an intricate network of distribution lines, transformers, substations, and meters, designed to ensure an efficient and reliable electricity supply to consumers. Over the years, the distribution system has undergone significant transformations, from the pre-privatization era, marked by state control and inefficiencies, to the post-privatization period, characterized by private sector involvement and attempts at reform. The DisCos are responsible for delivering electricity to end-users and stepping down high-voltage electricity from the transmission grid to low-voltage power usable by consumers. DisCos play a critical role in the electricity supply chain, connecting electricity consumers and the electricity grid. Due to their position in the supply value chain, DisCos are also responsible for billing consumers and collecting revenue. Ideally, DisCos should decide which substations receive electricity from the grid, but challenges often force them to compromise on this logic.
Despite their critical role, DisCos face significant challenges, including substantial Aggregate Technical, Commercial, and Collection (ATC&C) losses, as well as limited access to finance. DisCos experience substantial ATC&C losses daily due to poor distribution infrastructure, poor billing systems, electricity theft, and non-payment of electricity bills. The average ATC&C losses are estimated at 58.91 per cent (*NIGERIAN ELECTRICITY REGULATORY COMMISSION*, n.d.). These losses have severe implications for the financial sustainability of DisCos, hindering their ability to invest in infrastructure upgrading and expansion and ultimately affecting the reliability and efficiency of electricity supply to consumers.

Challenges Faced by Nigeria's Distribution System

Despite efforts at reform, Nigeria's distribution system continues to face numerous challenges that impede its efficiency and reliability. One of the critical challenges is poor infrastructure maintenance, which has resulted in frequent service interruptions and outages in the distribution network. Many DisCos struggle to maintain and upgrade their distribution infrastructure due to limited financial resources, inadequate technical expertise, and bureaucratic hurdles. Ageing equipment, frequent breakdowns, and substandard maintenance practices have become endemic in the distribution system, resulting in reduced electricity supply and decreased customer satisfaction. Another visible and recurring challenge is the combination of technical and commercial losses. High technical losses stemming from transmission and distribution losses remain a significant challenge in Nigeria's distribution system, resulting in reduced electricity supply and decreased revenue for DisCos. Inefficient equipment, voltage regulation issues, and electricity theft contribute to technical losses, while commercial losses result from billing inaccuracies, meter tampering, and non-payment of electricity bills. These losses have severe implications for the financial sustainability of DisCos, hindering their ability to invest in infrastructure upgrading and expansion and ultimately affecting the reliability and efficiency of electricity supply to consumers.
Electricity theft and non-payment are also significant challenges facing the NDS. Electricity theft, meter bypass, and non-payment of electricity bills by consumers pose tremendous challenges to DisCos, resulting in revenue losses and affecting their ability to invest in infrastructure upgrades

and maintenance. These issues also result in reduced electricity supply, decreased customer satisfaction, and increased energy costs. Furthermore, a lack of investment is a significant constraint in this sector. Limited investment in distribution infrastructure and capacity constraints hinder the ability of DisCos to meet the growing electricity demand, resulting in reduced electricity supply and decreased customer satisfaction. The complaints received by discos is represented in Figure 3. Metering, service distruption and billing took over half of the chunk of the complaints received. Other challenges facing the NDS include overloaded distribution networks, voltage imbalances, and sudden load changes, which reduce reliability and stability, triggering grid collapses and widespread power outages. In recent years, there has been an increase in available electricity generation capacity, resulting in a rise in electricity supply. As shown in Figure 4 and Figure 5, the average hourly generation of available units increased by +12.98% from 3,924.28 MWh/h in Q3 of 2023 to 4,433.82 MWh/h in Q4 of 2023. The total electricity generated in the quarter also increased by 12.98% (+1,125.05 GWh) from 8,664.82 GWh in Q3 of 2023 to 9,789.87 GWh in Q4 of 2023 (*2023_Q4_Report_Final-1.Pdf*, n.d.).

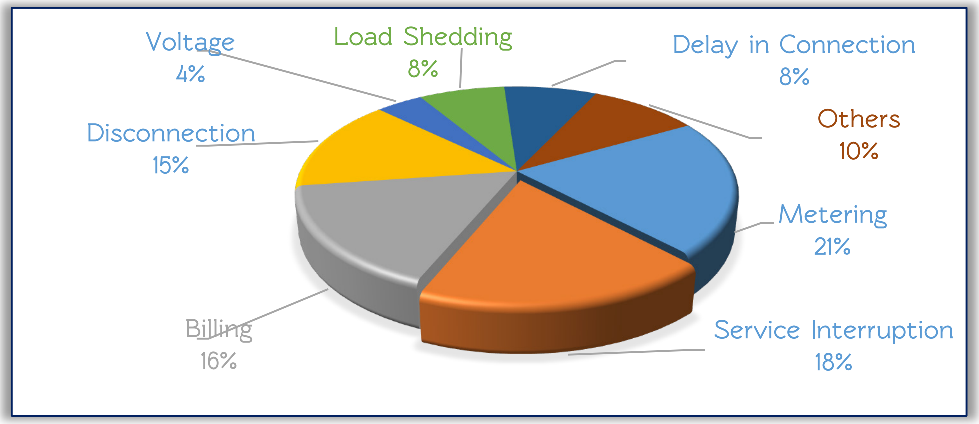

Figure 3. Major Complaints Received by DisCos in 2021

This increase in available generation capacity has resulted in a calculated balance between demand and supply, underscoring the need for continued investment in expanding generation capacity and upgrading infrastructure. To address the challenges facing the NDS, there is a need for prospective solutions, including the promotion of decentralized electricity generation through solar power and microgrids. Nigeria has abundant solar resources, making solar power a viable solution for decentralized electricity generation, particularly in remote and underserved areas. Furthermore, promoting distributed generation through rooftop solar installations can empower communities and reduce reliance on centralized grids. In addition, implementing microgrids emerges as a transformative solution, particularly in rural or underserved areas. Microgrids offer a decentralized approach to energy distribution, utilizing a combination of renewable energy sources, energy storage, and demand management techniques to provide a consistent power supply, even during grid outages.

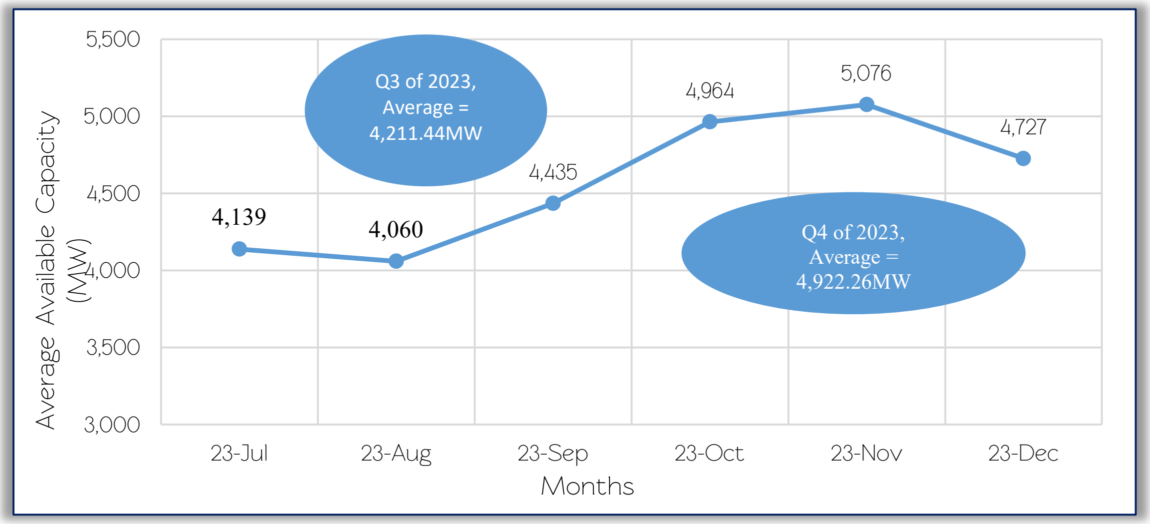

Figure 4. Available Capacity (July – December 2023)

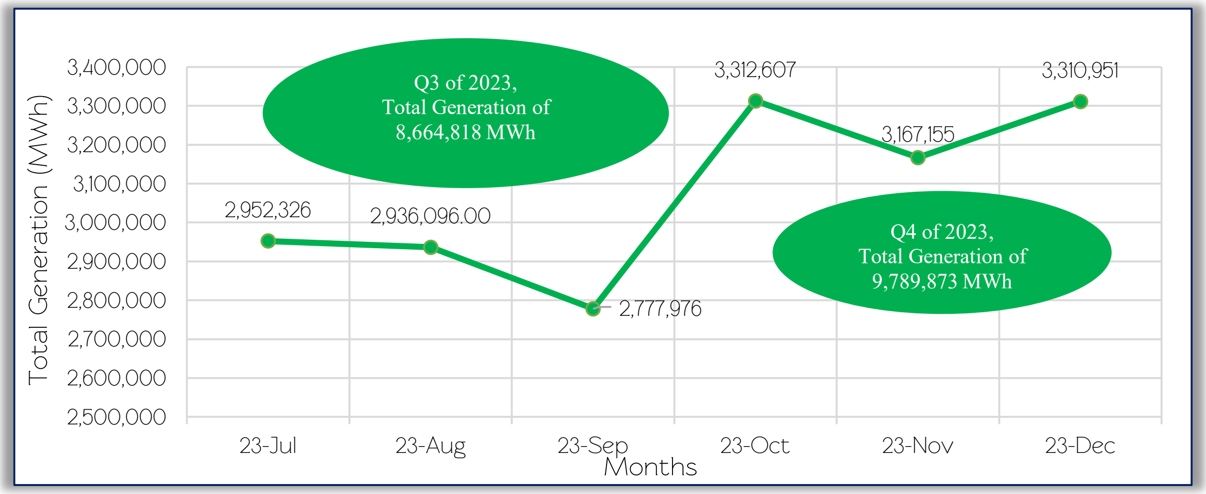

Figure5. Total Generation (July – December 2023)

In Q3 and Q4 2023, meter-penetration analysis revealed stark contrasts across distribution zones. The Yola Distribution Company registered metering rates below 30 %, indicating that fewer than one in three service points had functioning meters, severely limiting load monitoring, revenue protection, and demand-side management. By contrast, Ikeja DisCo exceeded 70 % penetration in both quarters, reflecting robust deployment of advanced metering infrastructure (AMI) and real-time data acquisition systems.

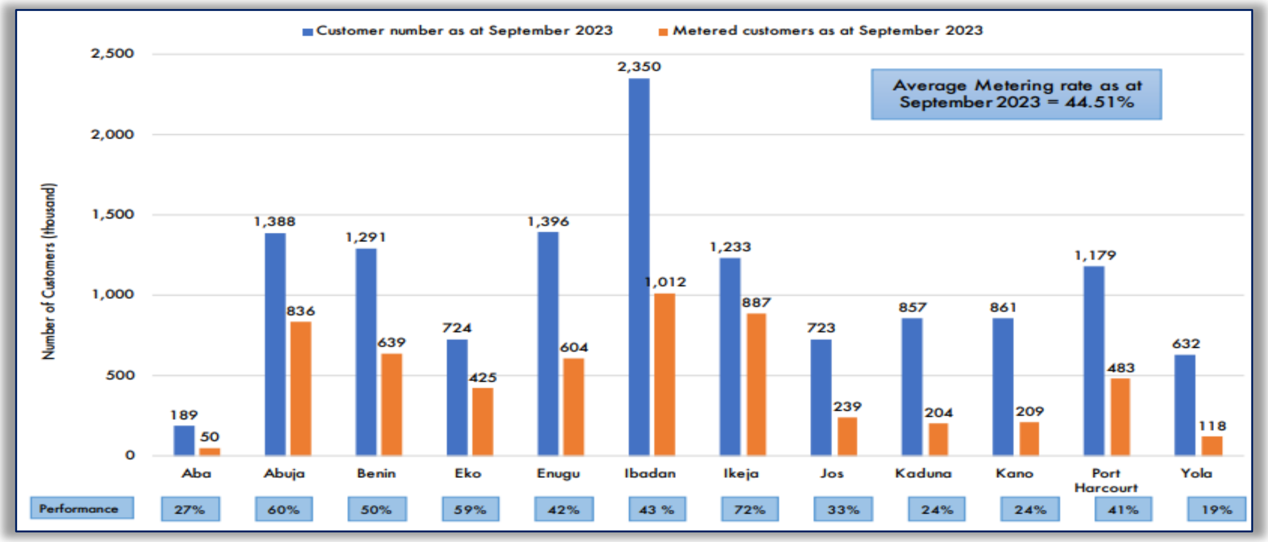

Figure 6. Status of Customer metering as of September 2023

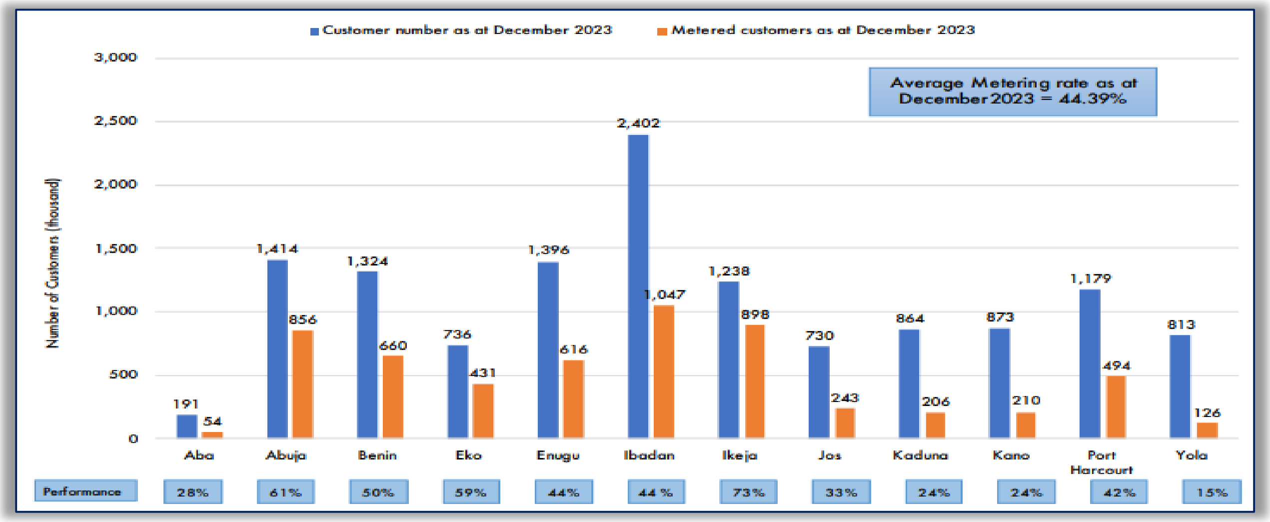

Figure 7. Status of Customer metering as of December 2023

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High meter coverage in Ikeja enables precise load profiling, dynamic tariff application, and rapid fault detection, directly contributing to lower Aggregate Technical, Commercial, and Collection (ATC&C) losses. Conversely, Yola's lagging metering undermines network optimization and revenue assurance, exacerbating technical losses and eroding financial viability. Targeting sub-40 % zones like Yola for accelerated AMI roll-out—with integrated prepayment meters and IoT-enabled data analytics—will be essential to harmonize metering performance nationwide and unlock the full benefits of smart-grid functionality. It is essential to note that the smart grid enables customers to participate in energy demand management. It is crucial to note that advanced metering infrastructure enables consumers to participate in demand programs, ensuring proactive maintenance and optimization. 148,389 meters were installed in Q3 of 2023, representing a decrease of 32,670 installations (-18.04%) compared to the 181,059 meters installed in Q2 of 2023 (*2023_Q4_Report_Final-1.Pdf*, n.d.). The prevalent issues, accounting for more than 78% of the total complaints during the quarter, were metering, billing, and service interruptions. Therefore, the supply of meters should be actively monitored with proper supply chain management to ensure every consumer's access.

5. KEY FINDINGS AND PROPOSED SOLUTION

Our comprehensive evaluation of Nigeria's transmission and distribution networks identifies seven critical barriers to reliable and efficient power delivery, along with a suite of targeted remedies to overcome them.

— Aging Transmission Infrastructure
(a) Finding: The Legacy 330 kV and 132 kV lines suffer from chronic underinvestment and deferred maintenance, resulting in frequent grid collapses and significant energy losses.
(b) Solution: Deploy dynamic line rating and reconductoring on high-voltage corridors, coupled with real-time condition monitoring, to increase ampacity, reduce thermal sag, and prevent bottlenecks.

— High Technical & Commercial Losses
(a) Finding: Inefficient conductors, voltage regulation failures, meter tampering, and billing inaccuracies extract over 30 % of generated energy, eroding utility revenues.
(b) Solution: Implement advanced metering infrastructure and theft-detection algorithms, enhance demand-response programs, and enforce anti-tampering regulations to recover lost energy and secure cash flows.

— Distribution Maintenance Deficit
(a) Finding: DisCos lack sufficient funds and skilled personnel for maintenance, resulting in frequent transformer failures, feeder overloads, and customer outages.
(b) Solution: Establish ring-fenced maintenance funds through public-private partnerships, institute certification programs for field technicians, and adopt predictive maintenance platforms that schedule upkeep based on equipment health indices.

— Revenue Erosion from Theft & Non-Payment
(a) Finding: Widespread meter bypass and unpaid bills deplete DisCo's capital, stalling reinvestment in network upgrades.
(b) Solution: Introduce prepaid metering with community education campaigns, integrate mobile payment gateways, and leverage smart grid analytics to flag anomalous consumption patterns.

— Under-Capitalized Network Expansion
(a) Finding: Limited financing and regulatory uncertainty hinder substation upgrades and feeder extensions, leaving peak demand (exceeding 25 GW) unmet.
(b) Solution: Craft transparent, investment-grade regulations and incentive structures, such as tax breaks for renewable co-location, to attract long-term capital into capacity expansions.

— Untapped Decentralized Generation
(a) Finding: Nigeria's 427 GW solar and significant wind potential remain largely unexploited, prolonging reliance on fragile central infrastructure.
(b) Solution: Promote community microgrids and rooftop PV through streamlined permitting, feed-in tariffs, and technical assistance programs, with a focus on off-grid and rural areas to alleviate grid stress.

— Smart-Grid Integration Gap
(a) Finding: The absence of SCADA upgrades and demand-response platforms prevents real-time load balancing and predictive fault detection.

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(b) Solution: Implement SCADA extensions, distribution management systems, and machine-learning-based load forecasting to optimize voltage profiles, manage peak demand, and forestall cascading failures.

6. CONCLUSION

Nigeria's power sector requires bold, integrated reforms that encompass grid modernization, advanced metering, regulatory overhaul, public-private partnerships, and workforce capacity building to overcome chronic outages, losses, and underinvestment. Our analysis identifies clear pathways, including upgrading transmission assets, deploying smart grid technologies, expanding decentralized renewable energy sources, and enforcing transparent policies, that can enhance efficiency, reliability, and customer trust. Policymakers and industry leaders should adopt these recommendations to guide targeted infrastructure investments, reduce energy losses, and accelerate economic growth. Scaled nationwide, this strategy will enhance energy access, reduce greenhouse gas emissions, and position Nigeria as a leader in sustainable, climate-resilient development.

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