



REVIEW ARTICLE

REVIEW OF SMART GRID TECHNOLOGY AND THE NIGERIAN ELECTRICITY
ACT: ADDRESSING POWER SECTOR CHALLENGES THROUGH POLICY AND
INNOVATION

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ABSTRACT

Energy policy plays a crucial role in shaping the energy landscape of any region. The reform of the Nigerian Electricity Act in 2023 marked a significant milestone for the Nigerian electricity market. It established a legal foundation aimed at addressing the nation's perennial energy crisis by enabling the adoption of modern sustainable technologies and initiatives into the Nigerian power industry. Poor policy implementation, inadequate generation, and unplanned downtime due to faults on the defunct transmission and distribution networks have stifled the growth of power delivery in Nigeria, emphasizing the need for more intelligent and sustainable power infrastructure. This paper presents a comprehensive review of the challenges in Nigeria's power sector and explores how emerging technologies can provide effective solution at every node of the power chain. It draws insights from global case studies and outlines a strategic roadmap and timeline for planning and implementing smart grid and sustainable initiatives in Nigeria. Additionally, it highlights critical considerations necessary to promoting long-term sustainability within Nigeria's power industry.

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1.0 Introduction

Energy poverty refers to the inability to access or afford reliable and safe power resources and services. In 2023, the World Health Organization (WHO) estimated that 2.4 billion people globally experience some form of energy poverty, emphasizing the pervasive nature of the issue (World Health Organization, 2024). Nigeria, the most populous African nation, is endowed with abundant natural resources, including solid minerals, petroleum reserves, coal, and renewable energy sources (Pontianus and Oruonye, 2021). Despite these resources, the country still struggles with energy instability, unreliable grid infrastructure, and underutilization of its energy resources, alongside the steadily increasing demand for electricity. The unreliability of Nigeria's national grid is primarily due to frequent outages and unplanned downtimes, often resulting from faulty or aging transmission and distribution equipment. Additionally, inefficiencies within major gas and thermal power plants further exacerbate the situation. According to the Transmission Company of Nigeria (TCN), the national grid experienced 12 collapses in 2024 alone, and recorded 105 cases of grid collapse between 2015 and April 2024 (Izuaka, 2025). With restoration times lasting a few hours and others extending up to three days, leading to extended blackout periods and significantly affecting businesses and other daily activities. Alao and Awoyele (2018) criticized the poor and myopic design of Nigeria's transmission network, describing it as the weakest link in the country's power chain, due to years of paltry upgrades.

While studies have examined the root causes of Nigeria's energy challenges and proposed several mitigation recommendations, there exist a gap for research that specifically examines how modern power technology can be adapted to address Nigeria's unique technical, environmental, and socio-economic climate. This study aims to analyze recent reforms in the Nigerian energy sector, highlighting key policy developments and innovation that foster sustainable growth. It identifies the most suitable smart devices and initiatives for Nigeria's current energy situation and presents them in a clear and actionable implementation plan. By drawing on insights from carefully selected global case studies, this study assesses the impacts, benefits, and potential bottlenecks of integrating advanced technologies into Nigeria's power grid.

This paper is structured as follows, the remainder of this section reviews important topics about the Nigerian power industry examined in literature, while the next provides an overview of the Nigerian Electricity Act 2023 and smart grid technology. Section three presents global case studies where smart devices have been successfully deployed to address similar energy challenges, and outlines a strategic implementation plan tailored to Nigeria's energy needs. The final section offers practical recommendations and concludes the paper.

1.1 Inefficiencies in Distribution Networks and Power Generation Issues

The Electric Power Sector Reform Act of 2005 established the Nigerian Electricity Regulatory Commission (NERC) and unbundled power services in Nigeria into 18 companies: 9 generation companies, 1 transmission company, and 11 distribution companies, popularly known as DisCos. The Ibadan Electricity Distribution Company (IBEDC) is the largest DisCo (based on numbers of registered customers) operating across seven states and serving over 2.5 million active customers (Sasu, 2024). In a research to analyze the performance of IBEDC's distribution network Abanihi and Ikheloa (2018) obtained reliability indices: SAIDI = 2,470.16 hours/year, SAIFI = 695.16 interruptions/year interruptions per customer, and ASAI = 71.88%. These reliability indices accentuate the inefficiencies in Nigeria's transmission and distribution infrastructure, and speak to the frequency and duration of power outage experienced in Nigeria. These frequent faults and outages have led to widespread customer dissatisfaction, damage to power equipment, and substantial loss of revenue for power companies (Patrick *et al.*, 2013). In addition, internal conflicts within power companies, particularly due to dissatisfaction of power workers with wages and working conditions, often result in subpar service delivery, and in some cases, partial blackouts triggered by industrial actions led by aggrieved labor unions. Similarly, oil and gas sector workers have on several occasions resorted to strikes to express grievances, disrupting gas supply to power generation plants. These disruptions significantly reduce generation capacity, thereby affecting the availability of power on the grid. In April 2025, the committee of power generation companies in Nigeria threatened to shut down operations, due to unpaid debts amounting to over ₦4 trillion. This incident underscores the growing frustration experienced by investors and power providers, who continue to face significant financial risks in the sector (Enietan-Matthews, 2025).

1.2 Nigeria's Sustainability Objective

With a current generation capacity of approximately 4,500 MW, and an annual electricity production of 42,509 GWh, the country's per capita electricity consumption remains low at around 144 kilowatt-hours (kWh) per person per year (World Bank, 2025). In response, the Nigerian government is working to bolster its power sector by accelerating the construction and integration of renewable energy sources into the national grid, to achieve a more stable and sustainable electricity supply in line with its 30:30:30 vision (Bugaje *et al.*, 2022). This goal necessitated the introduction of a reformed legal framework, the Electricity Act 2023 (Federal Ministry of Power, 2023 and Adu and Olawepo, 2023). The purpose of this legislation was to promote the diversification of Nigeria's energy mix, and reduce overreliance on natural gas, which currently accounts for over 75% of electricity generation, and also bring the country closer to meeting its growing energy needs.

Several scholars have investigated Nigeria's perennial energy challenges by examining their root causes, identifying structural inefficiencies, and exploring potential interventions to address Nigeria's energy poverty. In a bid to improve grid performance, Adaramola (2014) assessed the feasibility of grid-connected solar generation in a community in northern Nigeria. The study proposed an 80 kW solar plant optimized using HOMER software. To demonstrate the technical and economic viability of this project, a levelized cost of energy (LCOE) of \$0.103/kWh was achieved, proving more cost-effective than conventional diesel generators. These findings suggest that similar grid-connected solar PV systems could be economically feasible in other parts of Nigeria, especially in regions with high solar radiation. However, challenges such as high upfront costs, absence of efficient storage facilities, seasonal variability, and transmission losses were identified. Other researchers also conducted comparative analyses proposing hybrid systems that integrate standalone minigrids into the national grid to increase renewable energy (RE) penetration (Ekpe and Umoh, 2019). While such systems offer considerable benefits like improved grid capacity and resilience, the high capital requirements for grid extensions justify the continued reliance on insular minigrids, particularly in rural communities. Similarly, Adeniyi (2019) and Amuta *et al.* (2018) argued that integrating RE sources into the grid would enable the system to better manage peak demand and reduce dependence on gas. Adedokun *et al.* (2023) provided insights into on-grid renewable energy planning and highlighted the crucial role of government in this process. They observed that despite several ambitious RE goals, there has been little tangible progress in implementation, due to lack of accountability and transparency within government institutions. They also identified outdated policies, excessive bureaucracy, poor planning, and technological limitations as key barriers to achieving these goals (Nwozor *et al.*, 2021 and Akinyele and Rayudu, 2016). Ozoegwu *et al.* (2017)

emphasized the importance of policy-driven incentives, such as net metering and renewable portfolio standards, to stimulate broader adoption of RE by rewarding generation, supply, or consumption of renewable energy. Ibe and Okedu (2009) advocated for decentralized power generation, citing advantages such as lower emissions, higher grid stability and reliability, reduced fault rates, and ease of maintenance. Owebor *et al.* (2021) also proposed the use of carbon capture technologies to enhance the efficiency of gas and thermal power plants, stating that reduced CO₂ emissions from plants can promote Nigeria's climate objectives.

1.3 Role of Energy Policy

Numerous studies have also emphasized the importance of adequate energy policy in advancing Nigeria's power sector. Ozoegwu and Akpan (2021) acknowledged recent policy progress in Nigeria's power sector but argued that poor policy implementation limits the effective utilization of available energy sources, citing bureaucratic obstacles such as delays in licensing and standardization as major barriers to RE expansion. They also advocated for climate-specific technological research and the development of local manpower through technical skill acquisition programs. Furthermore, Edomah, *et al.* (2017) argued that effective policy formulation and implementation would attract private investment in power industries by curbing illegal connections and meter tampering, which result in revenue loss and deterrence of potential investors (Arowolo and Perez, 2020). Adelaja (2020) identified financial constraints by as a key impediment to RE deployment. He opined that the high upfront cost of renewable projects discourage investment, particularly given the long payback periods, and recommended government intervention to boost investor confidence through more favorable returns on investments and implementation of policies that allow for shorter recovery periods. Poor maintenance culture, diversion of funds, and corruption within agencies also severely stifle progress in the energy sector (Fabiye *et al.*, 2016). Another challenge is the lack of continuity in governance (Dioha *et al.*, 2019). Akinyele *et al.* (2019) observed that frequent changes in administration often lead to abandoned energy projects, impeding long-term progress.

1.4 Democratization of Electricity

Public participation has been identified as a strategy to improve power service delivery in Nigeria by getting citizens more involved in the generation, transmission, and distribution processes. Adhekpukoli (2018) advocated for the democratization of electricity in Nigeria by decrying the improper management and maintenance of public electric utilities. He cited various advantages of smaller stand-alone power solutions and argued that this approach could help alleviate power theft, vandalism of power infrastructure, and meter tampering, while promoting accountability and a stronger sense of ownership among citizens. Moreover, Dada (2014) identified public reluctance to adopt new technologies as a significant barrier to energy transition. Stating that most consumers tend to favor cheaper, short-term options such as gasoline generators over cleaner, long-term alternatives like solar power. The study, which included extensive interviews with industry leaders and policymakers, highlighted the need for targeted awareness campaigns to educate the public on the long-term economic and environmental benefits of clean energy adoption.

1.5 Need for Advanced Technology

Insufficient and outdated data is another roadblock to RE project planning and development in Nigeria. Brimmo *et al.* (2017) posited that without reliable data, accurate assessment and effective planning, RE projects become nearly impossible. This study stressed the need for advanced technologies to improve data acquisition in support of energy planning, research, and power system development (Vincent and Yusuf, 2014 and Oyewo *et al.*, 2019). Using Geographic Information System (GIS) tools, Mentis *et al.* (2015) conducted a location-based analysis of electrification patterns in rural areas of Nigeria. This assessment considered parameters such as existing transmission infrastructure, population density, mineral reserves, and proximity to urban centers. With these parameters, they developed an electrification model using Visual Basic to recommend the most viable power solutions for each area examined in their research.

2. The Electricity Act and Smart Grid Overview

2.1 The Electricity Act 2023

This reform serves as a legal and institutional framework for power operations and players within Nigeria. The objective of this act was to improve policy and regulatory structure to attract sustainable investment and promote renewable energy penetration in Nigeria Electricity Supply Industry (NESI). In 2023, renewable energy sources contributed less than 2% to the Nigerian energy mix, this policy reform was engendered to

remedy this deficiency, address the aging power infrastructure, and also revamp existing power plants, while attracting investments for efficient and cleaner power generation.

2.1.1 Key innovations of the Electricity Act 2023

- Creation of state electricity markets (Sections 63(1), 230(2-9)): This reform allows for the decentralization of power within the country, permitting states to regulate electricity activities and operations within respective jurisdiction.
- National Electricity policy and strategic implementation plan (Section 3(1-3)): The reform made provision for the preparation and publication of the National Integrated policy by the federal government through the ministry of power, this publication is subject to review and revision at most every 5 years
- Smart grid and renewable energy generation (Section 66(1)): It allows for the construction, maintenance, and operation of an integrated smart grid within the country and for investments to be made for the expansion and integration of appropriate technology into existing transmission infrastructure. It encourages the development and utilization of renewable energy for generation of power, and also facilitate the integration of renewable energy into the national grid and distribution networks in accordance with industry standards.
- Penalties for vandalism and electricity theft: This reform addresses the shortcomings of the previous power policies by criminalizing intentional damage to power infrastructure, unauthorized bypass with overhead or underground cables, and unauthorized tampering of metering equipment. The TCN attributed most breakdowns in the year 2024 to activities of vandals on transmission infrastructure (Ojo, 2024). This provision was made to curb the current attack on electricity infrastructure by vandals attacking transmission lines, meters, and other critical infrastructure often affecting power services, causing temporary or permanent damage to these resources.

2.1.2 Implications of this reform –Abia state

While Nigeria's power challenges remain severe, recent developments suggest that improved energy policies are beginning to yield positive results in the power industry. On the 5th of March 2025, the TCN announced that it transmitted the largest amount of electricity since the inception of power delivery in the country, which serves as a harbinger of positive development in the power industry. This also shows that integrating renewable energy into the mix would bring Nigeria closer to matching its energy demand.

Due to the developments and allowances provided in the Nigerian Electricity Act 2023, Abia State has taken advantage of this reform and passed its own electricity bill to establish a competitive electricity market, and also create the Abia State Electricity Regulatory Authority (ASERA) as the regulatory body for power and energy in the region. The state has also commissioned a 141MW integrated energy project. Abia State has seen increased power supplying bolstering industrial activities and improved the quality of life of its people. However, the state still faces challenges due to insufficient and inconsistent gas supply to its power plants, and have since set sights on a more renewable and sustainable power solution for the future developments. These developments in the state serve as a paragon for other regions facing similar power challenges in the country, as some have since begun delegations to follow in the footsteps of Abia state to promote the development and improvement of the power situation in their region (e.g. Ogun State) (Ulom, 2024).

2.2 The Need for Smart Grid Technology

The conventional power grid allows one-directional flow of electricity from central generation stations to consumers. The power grid is made up of arrangements of power equipment, communication infrastructure, and other devices working together for protection, monitoring and control of power evacuated via the grid. Smart grid modifies the conventional grid by employing more intelligent devices at every node of the power chain, facilitating more reliable and efficient flow of power and information back and forth from the utility to consumers. Smart grid is equipped with the ability to handle uncertainties in scheduling, power transmission and distribution. It also has potential to integrate RE sources into the grid, for diversification purposes. This futuristic power infrastructure integrates perfectly with modern technology enabling wide area awareness, grid visualization, real time data acquisition, and digital modelling. While also taking advantage of advancements in weather forecasts, GIS technology and artificial intelligence to improve power services and planning. The table 1 below gives a summary of Nigeria current electricity situation and emphasizes the need for improvements to minimize network losses and diversify the energy mix through penetration of RE sources.

Table I: Key power figures in Nigeria (IRENA, 2023)

Parameters	Figures
Population	~233 million
Total land area	923,769 km ²
Energy Mix (by %)	Gas 75%, Hydro 23%, RE 2%
Electricity Consumption	149 TWh/yr
Electricity generation capacity	5000MW (available)
Overall network losses	46%

2.2.1 Deficiencies in the conventional grid

Smart grid addresses several deficiencies in the conventional grid by offering reduced downtime from power failures, significantly lowering operation and maintenance cost for power infrastructure. Smart grid also offers good management of peak demand periods, improving energy security and efficiency of distributed generation (NERC, 2024). Some of these deficiencies are exponentially increasing demand, insufficient supply: inefficient plant, unreliable gas supply, intermittency of hydro due to wavering water levels, transmission and distribution network losses (from Table I), poor peak demand management causing uneven and unnecessary load shedding, aging equipment and outdated technology and overdependence on Fossil fuel and high levels of pollution.

2.3 Architecture of Smart Grid

The architecture of the smart grid describes how smart components and technological improvement can be made, at all levels of power delivery. Smart grid architecture consists of several modules involving automation of transmission and distribution, system coordination, energy efficiency, distributed generation, renewable integration, storage mechanisms, smart home appliances, consumer participation, and Electric Vehicle (EV) charging (Momoh, 2012). These modules can be further grouped into generation, transmission, distribution, and consumer level as seen in figure 1.

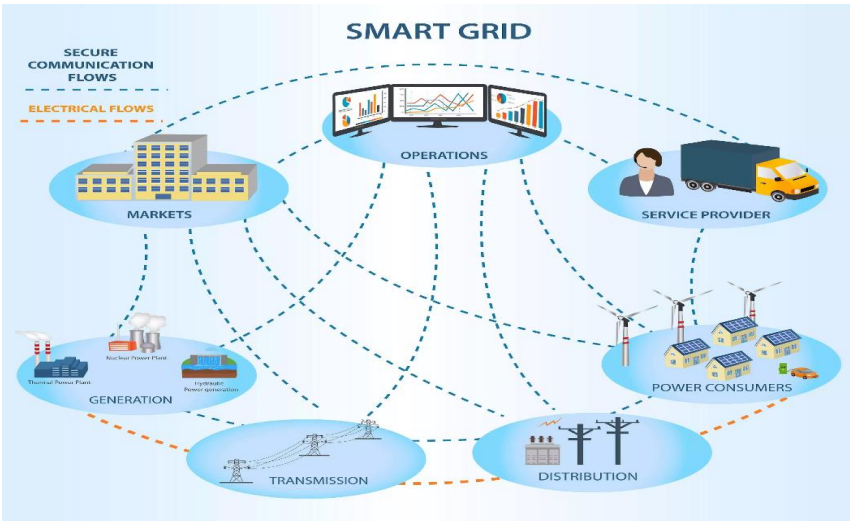


Figure 1: Power and information flow in a smart grid (Digiteum, 2021)

2.3.1 Generation level

Communication: The timely and secure exchange of important information within the generation plant and also with outside stations (central control centers and transmission stations) is crucial to maintaining the smooth operation of power delivery on the grid. Sensory and control devices must convey information of conditions and occurrences in real time within the plant to operators and engineers via a central monitoring system. These control devices also receive instructions from personnel about decisions to be carried out in the plant. Malfunctioning of these communication devices can reduce plant efficiency significantly and compromise the safety of personnel and plant equipment (Hu et al., 2019). Information must also be communicated with market operators for transparency and billing purposes.

Technologies like power line carrier communication, UHF and VHF radios are examples of conventional communication media for information exchange from plants to substations and control centers. However, their limitation in terms of range and bandwidth poses a major impediment to their continued usage. Others

like Fibre optic communication (OPGW) and IP- based SCADA are widely being adopted because of their high bandwidth and support for interoperability and automation, making them particularly complementary for smart grid operations and high-volume data exchange. Wireless sensor networks are also being considered to improve communication within the plants, while satellite communication solutions are in development for monitoring and communication for remote power generation applications.

Integration of Large-Scale Renewable Energy Solutions: Smart grid as a futuristic power infrastructure must efficiently integrate renewable energy sources into the mix, to be transmitted and distributed on the grid. This poses technical difficulty because of the intermittency and variation of these resources. Renewable energy sources experience fluctuations which are not generally associated with non-renewable sources, these fluctuations can cause voltage instability and distortions leading to more critical grid issues. For the integration of RE, adequate stochastic and prediction models must be developed to analyzing generation levels and demand patterns for design of better matching strategies. DC renewable sources like solar and some wind generation systems may have to be converted and synchronized with AC grid (as most transmission and distribution systems are AC networks) using special inverters synchronizer switches, and filters to alleviate harmonics and deliver quality power to consumers.

2.3.2 Transmission level

Metering, Monitoring and Control equipment: Transmission infrastructure is a crucial member of an integrated power system. It transmits high power from generation stations to major substations and load centers. For efficient, reliable, and stable transmission of power, advanced technology must be employed to monitor and control activities on the grid. Data must be acquired in real time for state estimation, stability assessment, fault detection and other important analyses of grid health condition. Tools like Supervisory Control and Data Acquisition (SCADA), Phase Measurement Units (PMU) and Wide Area Monitoring Systems (WAMS) are necessary at this level.

WAMS are utilized in transmission networks in smart grid systems to monitor and prevent the spread of disturbances on the grid. They utilize smart sensors placed strategically on the network gathering real time information that reflect general stability and health of the system. WAMS therefore allow for integration of modern computational and intelligence tools on the grid, like digital twin technology and software applications equipped with artificial intelligence competencies to achieve better grid performance (Cioara *et al.*, 2021 and Momoh, 2012).

PMUs are devices consisting of bus voltage and branch current phasors that measure voltage, current, and frequency on the transmission network. Using this data, they instantaneously compute voltage and current magnitude, phase angles, real and reactive power. These real time measurements by the PMU alongside competencies of WAMS and State estimators (SE) allow operators and engineers assess voltage stability and frequency disturbance in the entire power system, or on a section of the grid. State estimation is used to locate and deal with errors in measurements due to device malfunction or network errors, they also help in congestion management by providing justification of information obtained from the control and sensory devices on the grid, promoting adequate technical and economic decisions and also assisting with early detection of voltage transient stability issues. To achieve effective monitoring and controlling of the exchange of power in real time, smart grid needs the transfer of adequate and accurate information via a high speed two way communication technology from the utility to end users. Transmission substations must be in continued communication with generation stations and control centers via a wide area network, there must also be remote terminal units to enable communication with substation equipment, smart devices and controllers in the transmission substation using a Local Area Network.

Transmission stations can use both wired and wireless communication equipment depending on the application. These communication infrastructures must possess high bandwidth, and some form of encryption and cyber security firewall to prevent malicious attacks and infringement on the sensitive information. Examples of these technology are: optical fiber, broadband over power lines (BPL), multipoint spread spectrum, multiprotocol label switching (MPLS), and mesh technology.

2.3.3 Distribution level

Distribution automation (DA): Distribution is the flow of power from smaller substations (distribution substations) to consumers (residential, commercial, or industrial). In the smart grid architecture, DA is the

control of grid distribution equipment, distributed energy sources, energy storage facilities, and other grid integrated equipment to deliver quality power to consumers with minimum loss and disruptions.

Advanced Metering Infrastructure (AMI): AMI is the communication infrastructure connecting consumers' smart meters to distribution control centers. It enables two-way flow of information from smart meters to data management systems. AMI helps reduce labor and transportation cost for meter reading, it also improves accuracy and transparency of billing, displaying changes in electricity rates based on time-of-day and grid condition (Vijayan, 2023).

Clean Distributed Generation: Distributed generation involves the use of natural and sustainable means of power generation sited closer to consumers, to generate and distribute energy via the distribution network circumventing the complexities of central generation and transmission networks. Some examples include solar, wind, fuel cells, and small hydro. However, AC conversion and storage present concerns for distributed generation. Energy generated during time of peak generation must be stored as efficiently as possible and used when generation levels plummet (Maurizio *et al.*, 2014).

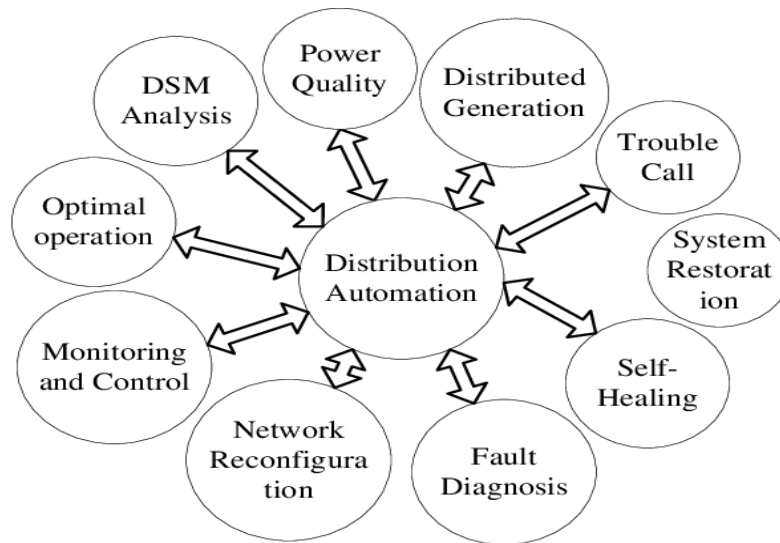


Figure 2: Major components of distribution automation (Salkuti, 2020)

Energy Storage Facilities: To improve the reliability of power, facilities are needed to store energy and deliver this stored energy when required. In the design of RE systems, storage facilities are necessary due to the intermittency of RE sources, and variations in weather and climatic conditions. They are also important due to the incongruity in time of peak generation of RE systems and the time of peak consumption (or demand). Some examples of such storage facilities are advanced batteries, superconducting magnetic energy storage, pumped-hydro, super capacitors, flywheels (Worku, 2022).

2.3.4 Consumer level

Smart Meters: Smart meters deployed on demand side provide information about consumption to customers, and also relay key data to utility in near real time, allowing for load control, peak load assessment, and appropriate pricing strategies. Additionally, smart meters enable utilities to connect and disconnect customers remotely and improve wide area monitoring of the grid. They also allow customers to monitor and control power consumption when integrated with home energy management systems (HEMS) (Momoh, 2012).

Smart Home Appliances and Demand Response Programs (DR programs): Home appliances like air conditioners, heaters, refrigerators, and washers can be equipped with smart chips that detect grid disturbance and turn off these appliances to allow stabilization of the grid. These devices are crucial to maintaining the stable function of the smart grid, they can also be integrated with smart meters to enable tax credits and better tariff options for customers that adopt these smart devices. DR programs allow the inclusion of customers in the process of energy efficiency to minimize consumption especially during peak hours. This initiative incentivizes customers who adjust activities and services that do not necessarily have to be done during peak hours and moving them to when renewable is at its peak, to benefit utility and stabilize the grid (Shewale *et al.*, 2020).

Home Power Solutions and vehicle-to-grid (V2G): Smart grid allows consumers with home renewable energy solutions to sell excess power to the utility via the grid and obtain incentives and benefits from governments or utility. When integrated properly this approach makes the grid robust and improves RE penetration on the grid. V2G serves as an alternative means of energy flow back to the utility during peak demand periods or other periods of stress or disturbance. Studies are still ongoing in regard to plug-in hybrid electric vehicles (PHEV) and its overall impact on the grid and the environment (Momoh, 2012 and Chen and Zhang, 2024).

2.4 Barriers to Smart Grid Adoption

Some barriers to the adoption of smart grid technology are high upfront cost, market uncertainty and public perception, lack of appropriate regulatory framework and technological limitations: communication and cyber security concerns.

3. Discussion

3.1 Global Case Studies

Table 2 shows examples where smart devices and sustainable initiatives have been applied to mitigate similar power challenges and the results achieved.

Table 2: Countries, their energy challenges, and result after addition of smart devices

Country	Challenges faced	Smart solutions	Results
USA (Sustainability Directory, 2025 and Amin and Schewe, 2008]	<ul style="list-style-type: none">•Frequent blackouts•Peak demand overload•Poor situational awareness during extreme weather conditions	<ul style="list-style-type: none">•PMUs and WAMS•DR programs and AMI•Automated fault management	<ul style="list-style-type: none">•Early detection of instability and accurate state estimation•Reduced peak demand and cascade failures
Japan (St-John, 2012, KBV Research, 2024 and Haslam, 2015)	<ul style="list-style-type: none">•Power shortage, overreliance on fossil fuels, and voltage fluctuations•Intermittent renewables and disaster risk.	<ul style="list-style-type: none">•Smart meter, DA, and HEMS•Microgrid, V2G, and battery energy storage	<ul style="list-style-type: none">•Improved reliability with decentralized and island-mode power•Reduction of carbon emission
Germany (Agora-Energiewende, 2025, Häseler and Wulf, 2024 and Jendernalik et al., 2017)	<ul style="list-style-type: none">• Grid congestion• Renewable integration and variability of RE sources	<ul style="list-style-type: none">• Smart meter and DR tariffs• Battery energy storage systems (BESS), pumped-hydro	<ul style="list-style-type: none">• Better renewable integration and control with reduced operational cost• Reduced grid losses and better frequency control• Improved SAIDI
Australia (Campbell, 2024, IES and EWEC, 2023, Deign, 2021 and Zaghwan and Gunawan, 2021)	<ul style="list-style-type: none">• Voltage instability due to high rooftop solar penetration at low demand periods• Poor voltage control and overgeneration	<ul style="list-style-type: none">• Smart inverters• Grid-scale battery storage	<ul style="list-style-type: none">• Cost reduction in frequency control• Improved power quality and rapid fault detection
India (Zaheeruddin and Manas, 2014, Satapathy et al., 2024 and Reddy, 2017)	<ul style="list-style-type: none">• Reliability issues, high transmission and distribution losses• Faulty billing and energy theft	<ul style="list-style-type: none">• Solar microgrid system• Smart meter and AMI• ML-based theft detection	<ul style="list-style-type: none">• Lower network losses• Improved billing• Improved security of power and power equipment
South Korea [Lim et al., 2021, Renewable Energy World, 2011 and Kang, 2020)	<ul style="list-style-type: none">• Frequent blackout• Grid instability due to rapid RE and EV penetration• Frequency fluctuations	<ul style="list-style-type: none">• Smart energy storage system• Smart meter and AMI• Smart grid protection act	<ul style="list-style-type: none">• Improved frequency monitoring and control• Improved demand flexibility• Growth of national smart grid market
Canada (Nhede, 2021, McLean et al., 2022, Belanger, 2014)	<ul style="list-style-type: none">• Grid communication issues• Reliance on fossil fuels• Regulatory inconsistencies	<ul style="list-style-type: none">• Digital smart meters• RE adoption and BESS in rural areas• Smart grid standards	<ul style="list-style-type: none">• Enhanced two way grid communication• Grid resilience and remote energy management• Grid friendly DER deployment

3.2 Strategic roadmap for adoption of smart devices and sustainable initiatives in Nigeria

Table 3 presents a feasible structured path towards a cleaner, smarter, reliable, and decentralized power network in Nigeria. It involves engagements and negotiations amongst players and actors in the power industry, as well as gradual implementation of sustainable initiatives.

Table 3: Strategic implementation plan for sustainable energy in Nigeria

Duration	Smart Devices and Initiatives
Short-term (0-2 years): Planning and infrastructural improvement	<ul style="list-style-type: none">● Stakeholder engagement (regulators, DISCOs, investors, consumers)● Establishment of smart grid committee and standards by NERC● Financial Planning● Power planning, grid mapping, and Integration of existing large-scale renewables using smart inverters etc.● Commence a national data acquisition strategy using IoT sensors for future grid analytics● Start skills and capacity development for smart grid adoption● Upgrading and/or replacing outdated transmission and distribution equipment with smarter equipment
Medium-term (3-5 years): Deployment and digital transformation	<ul style="list-style-type: none">● Installation and rollout AMI, PMU, and WAMS for monitoring and control● Development and deployment of digital twins, distribution automation infrastructure with AI/ML capability for predictive maintenance and forecasting● Major upgrade to communication equipment● Adoption of smart home energy systems, smart appliances, and demand response programs
Long-term (6-10+ years): Scalability, optimization, and consumer-centric systems	<ul style="list-style-type: none">● Fully autonomous grid management in high density areas● Integration of V2G infrastructure and regulation● Continuous review of regulatory framework● Development of climate-resilient grid infrastructure● Integration of more energy storage facilities for stability

3.3 Key Considerations and Implications for Smart Grid Adoption in Nigeria

Environmental consideration: Eco-friendly power solutions are essential to meet present energy demands with minimal environmental impact. Several key environmental factors must be assessed for renewable energy solutions, such as site selection and power planning. Potential downsides such as noise pollution, battery waste, disruption of hydro ecosystems and wind patterns, land use concerns, and the long-term climatic impact of energy projects on host communities must be adequately accounted for.

Technical Consideration and Energy Policy Development: Qualified personnel must be engaged at every stage of procurement, installation, construction, and integration of smart devices into the grid. Thorough technical evaluation through research, pilot testing, and simulation is crucial to ensure adherence to international energy standards and protocols. In addition, local supervisory committee should be established to monitor progress and develop national smart grid codes and regulatory frameworks.

Financial Consideration: To attract local and international investment, clear well-structured financial plans and concessions must be made. Government incentives, such as targeted subsidies, loans, and grants are necessary to facilitate the rapid growth of local green energy initiatives. Dedicated budget allocations for energy transition efforts will also boost investor confidence and promote sustainable development.

Public Acceptance and Socio-Economic Considerations: Citizens being primary stakeholders, must be actively involved in the energy transition process. Policies should prioritize consumer needs and promote public awareness to encourage acceptance and willingness to embrace newer power technologies. A progressive and inclusive approach should be used, to ensure equitable access, promote dialogue, and enable the smooth and gradual integration of smart grid initiatives in the country.

4. Conclusion

Smart grid technology facilitates the adequate flow of critical information and power on the grid and allows better monitoring and control to curb inefficiencies in transmission and distribution networks, while also enabling the integration of renewable energy sources into the grid. It has the potential to greatly improve the reliability, stability, and quality of power delivery in Nigeria. This study broadly reviewed Nigeria's power challenges and highlighted the role smart grid technology in alleviating them. It also proposed a strategic implementation timeline for the integration of smart devices and sustainable initiatives and provided necessary considerations to promote long-term energy development in Nigeria.

Nigeria has made huge strides towards attaining a sustainable energy infrastructure with the reform of its Electricity Act, providing a strong legislative framework for developments in its power sector. This reform was created to combat energy concerns like vandalism of power infrastructures, aging equipment, poor electricity access, and lack of transparent billing strategies, and to also make way for sustainable investment opportunities in Nigeria's power sector. However, it remains to be seen if this policy will be effectively enforced.

Efforts must be put towards ensuring timely implementation and continuity of energy projects. Nigeria's energy policy should also be continuously reviewed to reflect current needs and energy objectives, and to encourage more public participation in the power sector. To meet its energy goals, Nigeria must treat research and development in energy centers and institutions as top priority. Adequate funding must be available, to foster advancements in local manufacturing, material science, power electronics, and other important power systems research areas.

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