



AI-POWERED SMART GRIDS: OPTIMIZING ENERGY SYSTEMS IN DEVELOPING COUNTRIES – NIGERIA AS A CASE STUDY

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ABSTRACT

The global transition toward sustainable and resilient energy systems necessitates the modernization of legacy power infrastructure into intelligent, self-healing Smart Grids. While developed nations focus on integrating distributed renewable energy, developing countries face the more fundamental challenge of addressing chronic grid instability, high technical and non-technical losses (NTL), and a significant energy access deficit. This paper investigates the transformative potential of Artificial Intelligence (AI) and Digital Twin (DT) technologies in addressing these unique challenges, using Nigeria as a critical case study. Nigeria, with its recurrent national grid collapses and estimated 40-50% total system losses, represents a microcosm of the energy crisis in the developing world. We review the application of AI/Machine Learning models, such as Convolutional Neural Networks (CNN) and Long Short-Term Memory (LSTM) networks, for enhancing load forecasting accuracy in volatile demand environments (Eya, 2023; Gafai, 2022). Furthermore, we detail the use of AI-driven anomaly detection for combating pervasive NTL (electricity theft and meter bypass), a major financial drain on the sector (Hashim et al., 2024). The paper then explores the role of Digital Twin technology in creating virtual, real-time replicas of aging transmission and distribution assets, enabling predictive maintenance, optimizing asset life-cycle management, and simulating the impact of new infrastructure on the unstable grid. Finally, we analyze the critical implementation barriers, including data scarcity, human capital deficits, and institutional inertia, and propose a phased, data-centric policy roadmap for the successful adoption of AI-powered Smart Grids in Nigeria and similar developing economies. The convergence of these advanced digital technologies offers a viable pathway to achieving grid stability, reducing losses, and ultimately closing the energy access gap.

1.0 INTRODUCTION

1.1 Global Energy Transition and the Smart Grid Imperative

The 21st century has brought an unprecedented confluence of challenges to the global energy sector: the imperative to decarbonize energy sources to mitigate climate change, the need to

accommodate decentralized and intermittent renewable energy sources (RES), and the growing demand for reliable, high-quality power. The traditional, centralized power grid architecture is ill-equipped to handle these complexities. Consequently, the concept of the **Smart Grid**—an electricity network that uses digital communication technology to detect and react to local changes in demand and supply has become the global standard for modernizing power infrastructure. Smart Grids promise enhanced efficiency, improved reliability, and the seamless integration of distributed energy resources (DERs) (Eleks, 2024).

1.2 The Unique Context of Developing Countries

While Smart Grid deployment in developed nations primarily focuses on optimizing the integration of high-penetration renewables, the context in developing countries is fundamentally different and often more challenging. Nations in sub-Saharan Africa, South Asia, and parts of Latin America grapple with a legacy of aging, poorly maintained infrastructure, chronic power deficits, and pervasive system losses (Belge et al., 2024). The core objective is not merely optimization but achieving basic grid stability and extending energy access to underserved populations.

Nigeria, as Africa's largest economy and most populous nation, serves as a compelling and critical case study. Despite vast natural gas reserves and significant installed generation capacity, the country suffers from a severely constrained and unreliable power system characterized by frequent grid collapses, high operational costs, and a massive energy access gap, with millions relying on expensive and polluting self-generation (Onakowoicho, 2025). The successful application of advanced digital technologies in Nigeria could provide a scalable blueprint for energy sector transformation across the developing world.

1.3 AI and Digital Twin as Transformative Technologies

The recent advancements in Artificial Intelligence (AI) and Digital Twin (DT) technologies offer powerful tools uniquely suited to address the systemic failures of developing-world grids. AI, particularly Machine Learning (ML) and Deep Learning (DL), excels at pattern recognition, prediction, and anomaly detection—functions directly applicable to optimizing grid operations, forecasting volatile load, and identifying system inefficiencies. The Digital Twin, a virtual, real-time replica of a physical asset or system, provides a risk-free environment for simulating complex grid interactions, testing optimization strategies, and enabling highly accurate predictive maintenance (ConsultQE, 2025). This paper argues that the synergistic application of AI and DT is not merely an enhancement but a necessary foundation for the successful implementation of a resilient Smart Grid in Nigeria.

The scope of this review is to systematically analyze the application of AI and DT in three critical areas for the Nigerian power sector: optimization of energy systems (load forecasting), reduction of system losses (NTL detection), and management of aging assets (predictive maintenance and simulation).

2.0 The Nigerian Energy Landscape: Challenges and Opportunities

The Nigerian power sector is characterized by a complex interplay of technical, financial, and institutional challenges that have historically constrained its growth and reliability. Understanding this context is crucial for designing effective digital interventions.

2.1 Grid Instability and Collapse

The most visible symptom of the sector's fragility is the recurrent national grid collapse. The grid, managed by the Transmission Company of Nigeria (TCN), is often described as a

"nervous system" prone to frequent failures, sometimes collapsing multiple times a year (Olaniwun Ajayi, 2025). The root causes are multi-faceted:

- *Aging Infrastructure:* Much of the transmission and distribution network was built decades ago and has not been adequately maintained or upgraded to handle current load demands. The average age of key transmission assets often exceeds their design life, leading to frequent component failures.
- *Inadequate Transmission Capacity:* The transmission network acts as a bottleneck, unable to evacuate the full capacity generated by power plants, leading to generation curtailment and system instability. The radial nature of the grid, with few redundant paths, means that a single fault can cascade into a national blackout.
- *Lack of Real-Time Monitoring:* The absence of comprehensive, real-time Supervisory Control and Data Acquisition (SCADA) systems across the entire network hinders operators' ability to quickly diagnose and isolate faults, prolonging system blackouts. The TCN reports average transmission losses of 7.79 megawatts for every 100 megawatts transmitted, a figure indicative of systemic inefficiency (Reuters, 2024).

2.2 Technical and Non-Technical Losses (NTL)

Nigeria suffers from some of the highest system losses globally, estimated to be between 40% and 50% of generated power (Online Scientific Research, 2024). These losses are categorized as:

- *Technical Losses:* Power dissipated as heat during transmission and distribution, primarily due to aging equipment, undersized conductors, and long distribution lines. These losses are compounded by poor power factor and unbalanced loads.
- *Non-Technical Losses (NTL):* Losses due to commercial irregularities, including electricity theft, meter bypass, billing fraud, and uncollected revenue. NTL is a massive financial drain, undermining the financial viability of the Distribution Companies (DisCos) and discouraging private investment (Abro et al., 2025). Recent reports indicate that over 68% of consumers may be bypassing prepaid meters, highlighting the scale of the NTL crisis (The Electricity Hub, 2025). The financial impact of NTL is estimated to be in the billions of Naira annually, creating a vicious cycle of underinvestment and poor service delivery.

2.3 Energy Access and the Role of Decentralization

Despite being a major oil and gas producer, Nigeria has one of the world's largest energy access deficits. While the national grid reaches approximately 60% of the population, the power is often unreliable, leaving an estimated 86 million people without access to reliable electricity (IEEE Spectrum, 2025). This deficit has spurred the rapid growth of decentralized solutions:

- *Mini-Grids and Off-Grid Solutions:* Solar mini-grids and solar home systems are increasingly filling the gap, providing reliable power to rural and underserved communities. This decentralized model, while essential for energy access, adds complexity to future grid planning and integration. The Nigerian government's focus on mini-grids, such as the \$3.2 million solar mini-grid pilot, is sparking a clean energy revolution across emerging markets (Forbes, 2025).
- *Self-Generation:* Businesses and households rely heavily on diesel and petrol generators, leading to high operational costs, noise pollution, and significant carbon emissions. This reliance on self-generation further reduces the load on the national grid, making accurate forecasting more difficult and contributing to the financial woes of the DisCos.

2.4 Data Infrastructure Readiness

The foundation of any AI or DT implementation is data. Nigeria's power sector currently faces a significant data challenge:

- **Poor Metering:** The lack of universal smart metering means that consumption data is often estimated or based on manual readings, leading to inaccuracies and facilitating NTL. The current metering infrastructure is insufficient to provide the granular, real-time data required for advanced AI/DT applications.
- **Fragmented Data Systems:** Data collection is often fragmented across different DisCos and TCN, with limited standardization and real-time data exchange capabilities. This lack of a unified data platform is a major impediment to system-wide optimization and the creation of a comprehensive Digital Twin of the national grid.

Table 1. Nigeria’s power sector challenges

Challenge Area	Specific Problem in Nigeria	Impact on Grid	Digital Solution Focus
Grid Stability	Recurrent national grid collapses, aging T&D infrastructure	Frequent blackouts, economic disruption, generation curtailment	Digital Twin (Simulation, PdM)
System Losses	40-50% total losses, high NTL (theft, bypass)	Financial insolvency of DisCos, lack of investment	AI/ML (NTL Detection, Load Forecasting)
Energy Access	86 million people without reliable power, reliance on self-generation	Economic stagnation, environmental pollution	DT (DER Integration), AI (Microgrid Optimization)
Data Readiness	Poor metering, fragmented SCADA systems	Inaccurate forecasting, inability to detect real-time faults	Policy (Smart Metering), AI (Data Imputation)

3. AI APPLICATIONS FOR GRID OPTIMIZATION IN THE NIGERIAN CONTEXT

Artificial Intelligence (AI) and its sub-fields, Machine Learning (ML) and Deep Learning (DL), provide the computational intelligence necessary to transform raw grid data into actionable insights. In the Nigerian context, AI applications are strategically focused on mitigating the most pressing operational and financial challenges: volatile load, high non-technical losses, and poor asset reliability.

3.1 Load Forecasting and Demand-Side Management (DSM)

Accurate load forecasting is the cornerstone of efficient grid operation, directly impacting generation scheduling, reserve capacity planning, and operational costs. In Nigeria, load demand is highly volatile due to frequent grid outages, the reliance on self-generation, and unpredictable weather patterns. Traditional statistical models often fail to capture these complex, non-linear dynamics.

- **Advanced AI/ML Models:** Recent research has demonstrated the superiority of advanced ML models for load prediction in the Nigerian power system. Studies have successfully applied Artificial Neural Networks (ANN) for short-term load forecasting (STLF) in regions like Abuja, showing improved accuracy over conventional methods (Gafai, 2022). More sophisticated models, such as Convolutional Neural Networks (CNN) combined with Long Short-Term Memory (LSTM) networks (CNN-LSTM), are being explored to capture both the spatial and temporal dependencies in load data, which is crucial for predicting demand in a fragmented grid (Eya, 2023). The integration of external factors, such as socio-economic indicators and public holidays, further enhances the predictive accuracy of these models.
- **AI-Driven DSM:** Beyond forecasting, AI enables sophisticated Demand-Side Management (DSM). By analyzing historical consumption patterns, weather data, and real-time pricing signals, AI algorithms can predict peak demand events and automatically or semi-automatically adjust the load of participating consumers. This capability is vital for the

Nigerian grid, allowing operators to manage peak demand without resorting to load shedding, thereby improving stability and reducing the need for expensive, high-cost generation. AI can also optimize the charging and discharging cycles of battery storage systems, maximizing their contribution to grid stability.

3.2 Non-Technical Loss (NTL) Detection

Non-Technical Losses (NTL), primarily due to electricity theft and meter tampering, represent a major threat to the financial sustainability of the Nigerian power sector. AI/ML offers the most effective defense against this challenge by identifying anomalous consumption patterns that are invisible to manual inspection.

- *Anomaly Detection Models:* The core of AI-driven NTL detection is anomaly detection. This involves training models on historical, legitimate consumption data to establish a "normal" profile. Any significant deviation from this profile is flagged as a potential NTL event.
 - *Supervised Learning:* Models like Support Vector Machines (SVM) and Random Forests are used when a dataset of known fraudulent and non-fraudulent consumers is available.
 - *Unsupervised Learning:* Clustering algorithms, such as K-Means or DBSCAN, are employed to group consumers with similar consumption behaviors. Outliers that do not fit into any established cluster are then investigated as potential thieves.
- *Deep Learning for Feature Extraction:* More advanced approaches utilize Deep Learning, such as Stacked Autoencoders or Recurrent Neural Networks (RNNs), to automatically extract complex features from raw consumption time-series data, leading to higher detection accuracy and a lower false-positive rate (Hashim et al., 2024). The successful deployment of these systems is projected to significantly reduce the 40-50% system losses, injecting much-needed revenue into the DisCos for infrastructure investment. The use of federated learning is also being explored to allow DisCos to share NTL detection models without sharing sensitive customer data.

3.3 Fault Detection and Predictive Maintenance (PdM)

The aging infrastructure in Nigeria is highly susceptible to sudden failures, leading to localized outages and contributing to grid instability. AI-driven Predictive Maintenance (PdM) offers a proactive solution by shifting from reactive (fix-after-failure) or time-based (scheduled) maintenance to condition-based maintenance.

- *Sensor Data Analysis:* By analyzing data streams from sensors (e.g., temperature, vibration, oil quality) on critical assets like transformers and circuit breakers, ML algorithms can learn the "health signature" of the equipment.
- *Failure Prediction:* Models like Hidden Markov Models (HMM) or LSTM networks can predict the remaining useful life (RUL) of an asset, allowing maintenance to be scheduled precisely when needed, before a catastrophic failure occurs. This not only improves grid reliability but also optimizes maintenance budgets, a critical consideration for financially constrained utilities in Nigeria. PdM can also be applied to the transmission network by analyzing data from phasor measurement units (PMUs) to detect subtle anomalies indicative of impending line faults.

3.4 AI for Renewable Energy Integration and Microgrid Optimization

As Nigeria increases its adoption of solar and hydro power, AI becomes essential for managing the intermittency of these sources.

- *Forecasting Renewable Generation:* AI models can accurately forecast solar irradiance and wind speed, allowing grid operators to predict the output of renewable energy plants hours

or days in advance. This is crucial for maintaining the generation-demand balance and preventing frequency fluctuations that can lead to grid collapse.

- *Microgrid Control:* For the growing number of mini-grids, AI can optimize the dispatch of power between solar PV, battery storage, and diesel generators. Reinforcement Learning (RL) algorithms are particularly effective here, learning optimal control policies in real-time to minimize fuel consumption and maximize the use of clean energy, thereby reducing the cost of electricity for rural communities.

4. DIGITAL TWIN TECHNOLOGY FOR ASSET AND SYSTEM MANAGEMENT

While AI provides the intelligence for optimization, **Digital Twin (DT)** technology provides the virtual platform for simulation, testing, and real-time monitoring. A DT is a dynamic, virtual replica of a physical asset, process, or system, continuously updated with real-time data from its physical counterpart. For the Nigerian power sector, DTs are invaluable for managing aging assets and simulating the complex dynamics of an unstable grid.

4.1 Digital Twin Fundamentals in Power Systems

The DT concept is built on three pillars: the **Physical Asset** (e.g., a substation), the **Virtual Model** (a high-fidelity simulation), and the **Data Link** (real-time data flow between the two). In the context of the Nigerian grid, DTs offer a safe, virtual environment to:

- *Test Interventions:* Simulate the impact of a new transmission line or a major substation upgrade before physical construction begins.
- *Train Operators:* Provide realistic training scenarios for grid operators, including simulating grid collapse and recovery procedures.
- *Real-Time Monitoring:* Provide a unified, 3D visualization of asset health and operational status, overcoming the limitations of fragmented SCADA systems. The DT acts as a single source of truth for all asset information.

4.2 Application in Transmission and Distribution (T&D) Asset Management

The application of DTs to the T&D network is crucial for extending the life and improving the reliability of Nigeria's aging infrastructure.

- *Substation and Transformer DTs:* Creating DTs of critical substations allows for continuous, real-time monitoring of key performance indicators (KPIs) like temperature, load, and partial discharge. The DT can predict component failure with high accuracy, enabling PdM strategies that prevent catastrophic outages. This is particularly relevant for Nigeria, where transformer failure is a common cause of localized blackouts. The DT can also optimize the tap-changer settings of transformers to maintain optimal voltage levels and reduce technical losses.
- *Transmission Line Optimization:* DTs of transmission lines can be used to calculate Dynamic Line Rating (DLR). By incorporating real-time weather data (temperature, wind speed) into the DT, operators can determine the maximum safe current a line can carry at any given moment, often exceeding the static, conservative rating. This effectively increases the capacity of the existing transmission network without costly physical upgrades, a significant advantage for the TCN (ConsultQE, 2025). Furthermore, DTs can model the physical sag and tension of lines, preventing failures due to extreme weather conditions.

4.3 Digital Twin for Grid Planning and Simulation

The DT moves beyond individual asset management to system-level optimization, which is paramount for a grid prone to collapse.

- **Grid Collapse Simulation:** A DT of the entire national grid can be used to simulate various fault and collapse scenarios. By running these simulations, operators can identify weak points in the network, optimize protection settings, and develop automated, rapid recovery protocols to minimize blackout duration. This capability is essential for improving the resilience of the Nigerian grid.
- **Integration of DERs:** As mini-grids and solar farms proliferate, the DT becomes essential for modeling their impact on the main grid. It allows planners to simulate the effect of intermittent renewable generation on grid stability and design optimal interconnection points and control strategies for future grid-tied operations. The DT can model the bi-directional power flow introduced by DERs, a phenomenon the current radial grid was not designed to handle.

4.4 Synergy of AI and Digital Twin: The Closed-Loop Smart Grid

The true power lies in the synergy between AI and DT. This integration creates a **closed-loop control system** that is the hallmark of a truly intelligent grid.

- **AI-Enhanced DT:** AI models, such as those used for load forecasting (Section IV.1) and NTL detection (Section IV.2), provide the input data (predicted load, predicted NTL, predicted asset health) that drives the DT simulation. The DT uses these AI-derived predictions to run "what-if" scenarios, such as "What is the optimal generation schedule given the predicted load and the predicted NTL for the next 24 hours?"
- **DT-Trained AI:** Conversely, the DT generates vast amounts of synthetic, high-fidelity data that can be used to train and refine the AI models, especially in data-scarce environments like Nigeria. For instance, the DT can simulate thousands of grid collapse scenarios, generating labeled data that can be used to train an AI model to automatically detect and isolate faults in the real-world grid. This continuous feedback loop—AI informs the DT, and the DT trains the AI—is the mechanism for a self-improving, self-healing grid. This synergy is particularly critical in the Nigerian context where historical data is often unreliable or incomplete (Onile, 2024).

5. IMPLEMENTATION CHALLENGES AND POLICY RECOMMENDATIONS

While the technological potential of AI and Digital Twins is clear, their successful implementation in the Nigerian power sector is contingent upon overcoming significant non-technical barriers related to data, infrastructure, human capital, and governance.

5.1 Data and Infrastructure Challenges

The most immediate hurdle is the **data scarcity and quality deficit**. AI and DT models are data-hungry, yet the Nigerian grid operates with fragmented, often manual, and non-standardized data collection systems.

- **Lack of Smart Metering:** The absence of universal smart metering means that real-time, granular consumption data—the lifeblood of NTL detection and accurate forecasting—is largely unavailable. The current metering infrastructure is insufficient to provide the granular, real-time data required for advanced AI/DT applications.
- **Legacy SCADA Systems:** Existing Supervisory Control and Data Acquisition (SCADA) systems are often outdated, siloed, and lack the necessary communication bandwidth and security protocols to support real-time DT data feeds. Upgrading these systems is a massive capital investment challenge.
- **Communication Infrastructure:** The reliability and bandwidth of the national communication network (e.g., fiber optics, 4G/5G) in remote areas are insufficient to support the continuous, high-volume data exchange required for a fully operational DT of

the entire grid. Investment in a dedicated, secure communication network is non-negotiable.

5.2 Human Capital and Institutional Barriers

Technology adoption is only as successful as the people and institutions that manage it. Nigeria faces a critical shortage of specialized expertise.

- *Skills Gap:* There is a significant deficit in local talent proficiency in AI/ML model development, data engineering, and advanced power system control, particularly in the context of digital twin maintenance and operation. This necessitates a massive, coordinated effort in technical education and training.
- *Institutional Resistance and Inertia:* The transition from a manual, reactive operational model to an automated, data-driven one requires a fundamental cultural shift within the utility companies. Resistance to change, coupled with regulatory inertia, and the fear of job displacement can slow down the adoption of new technologies.
- *Governance and Corruption:* The high rate of NTL is not purely a technical problem, but a governance issue rooted in corruption and poor enforcement. Without addressing the institutional failures that enable electricity theft, even the most sophisticated AI detection systems will struggle to achieve their full impact. AI-driven NTL detection must be paired with robust legal and enforcement mechanisms.

5.3 Cybersecurity and Data Privacy

The digitalization of the grid inherently increases the attack surface, making cybersecurity a paramount concern.

- *Increased Vulnerability:* A fully interconnected Smart Grid, managed by AI and DTs, presents a single, high-value target for cyberattacks, which could lead to widespread blackouts or data manipulation. The risk of a coordinated attack on the national grid is significantly higher in a digitalized environment.
- *Lack of a Unified Framework:* Nigeria currently lacks a comprehensive, unified cybersecurity framework specifically tailored for critical national energy infrastructure that mandates security standards for all DisCos and the TCN.
- *Data Privacy:* The collection of granular consumption data for NTL detection and DSM raises significant data privacy concerns for consumers, necessitating clear regulatory guidelines and robust anonymization protocols. The framework must balance the need for data-driven optimization with the protection of consumer rights.

5.4 Policy Recommendations for Adoption

To successfully harness the potential of AI and DT, a multi-pronged policy and investment strategy is required:

6. CONCLUSION AND FUTURE WORK

The energy crisis in Nigeria, characterized by chronic instability, high losses, and a vast energy access deficit, demands a radical, technologically advanced solution. This review has demonstrated that the synergistic application of Artificial Intelligence and Digital Twin technologies offers a viable and necessary pathway to transform the Nigerian power sector from a fragile, loss-ridden system into a resilient, efficient, and financially sustainable Smart Grid.

Table 2. Policy Recommendation for Adoption

Recommendation Area	Specific Policy Action	Expected Outcome
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Data Foundation	Mandate universal, standardized smart metering across all DisCos within a five-year timeframe.	Provide real-time, high-quality data necessary for AI/DT implementation and NTL reduction.
Infrastructure	Prioritize investment in a dedicated, secure fiber-optic communication backbone for the TCN and critical substations.	Ensure reliable, high-bandwidth data transfer for real-time DT operation and grid control.
Human Capital	Establish specialized AI/Smart Grid training centers in partnership with local universities and international technology providers.	Develop the local expertise required to build, deploy, and maintain advanced digital systems.
Governance	Implement a transparent, performance-based regulatory framework that rewards DisCos for NTL reduction and grid stability improvements.	Align financial incentives with technological adoption and combat institutional resistance.
Cybersecurity	Develop and enforce a national cybersecurity standard for the energy sector, including mandatory penetration testing and incident response protocols.	Protect the digitalized grid from cyber threats and ensure system resilience.

AI-driven load forecasting and NTL detection directly address the core operational and financial failures of the current system, promising to stabilize the grid and recover billions in lost revenue. Simultaneously, Digital Twin technology provides the essential platform for simulating complex grid dynamics, optimizing the life-cycle management of aging assets, and safely planning the integration of decentralized energy resources.

However, the transition is not purely a technical one. Success hinges on a foundational commitment to data standardization, massive investment in communication infrastructure, and a concerted effort to build local human capital and overcome institutional inertia. The policy recommendations outlined herein provide a phased roadmap for the Nigerian government and utility companies to move beyond incremental fixes toward a comprehensive digital transformation.

Future research should focus on the development of AI-driven microgrid control systems tailored for the Nigerian context, the socio-economic impact analysis of NTL reduction on consumer behavior, and the creation of low-cost, open-source DT frameworks specifically designed for data-scarce developing economies. By embracing this digital revolution, Nigeria can not only solve its chronic power problems but also establish a scalable model for energy sector modernization across the developing world.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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