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## Real-Time Anomaly Detection for Nigerian Power Grid Stability: An Integrated Time Series and Machine Learning Approach

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### ABSTRACT

Among other endemic problems with the nation's grid, including frequent grid failure, load-shedding, poor generation, and old equipment, the Nigerian Electricity Regulatory Commission (NERC) has documented over 300 system breakdowns annually. This study was carried out using a multi-phase method that used synergy of residual analysis via ARIMA, statistical outlier isolation (via IQR), isolation forests, and seasonal decomposition (STL) in R language (v4.3.0) to detect anomalies in this sector. Three years of Transmission Company of Nigeria (TCN) and major distribution companies such as Lagos State Electricity Board (LSEB) and Abuja Electric Distribution Company (AEDC) electrical demand data were used in the modeling process. Some performance metrics used included F1-score, accuracy, recall, and identifying and locating anomalies with the assistance of a domain expert. The outcome indicates that the accuracy at identifying relevant abnormalities suitable for Nigerian grid conditions was 89.4%, and the recall rate was 84.2%. The statistical breakdown approach returned 234 meaningful anomalies, while the machine learning approach returned 198 anomalies with greater confidence. The system identified trends with respect to repeated grid collapse, alternating generators on outage, and unbalanced loads across 11 electricity distribution companies. It has strong anomaly detection from statistics alone as well as even with machine learning techniques, which may increase grid resilience and reduce the risk of cascading failures. With significant economic gains to Nigeria, field deployment can reduce unplanned outages by as much as 31%.

### INTRODUCTION

Nigeria's power infrastructure is one of Sub-Saharan Africa's most sophisticated yet underproductive grid systems. Being one of the largest economy on the African continent (World bank, 2024), with a population size of more than 220 million, its current installed generating capacity of some 12,500 MW is well short of its projected 30,000 MW required to cater for current demand (Nigerian Electricity Regulatory Commission [NERC], 2023). System crashes, with its national grid experiencing regular or total black-outs on a monthly basis, cost Nigeria's economy an approximated ₦126 billion in terms of productivity loss every year (Adenikinju, 2022, Okafor & Ejiogu 2023).

There were profound reforms on its power sector in 2013 through the privatisation of its generation and distribution companies, but some problems remain. Its grid complexity has only grown with the addition of independent power producers (IPPs), renewable energy, and distributed generation systems spread across its six geopolitical zones (Okoro *et al.*, 2023). Its traditional grid monitoring systems, with threshold-based alarms as well as manual inspections from the Transmission Company of Nigeria (TCN), are no longer capable of coping with the dynamic nature of Nigeria's evolving power landscape.

Grid instability in Nigeria is expressed in multifarious dimensions, from voltage oscillations and frequency excursions to abrupt rejections of load, leading to

widespread blackouts impacting millions of Nigerians. Its economic impact is not only confined to immediate loss on a short-term scale but also reaches into healthcare services, schools, productivity in industries, as well as small-scale enterprises that are the very bedrock of the Nigerian economy (Babatunde *et al.*, 2021).

### LITERATURE REVIEW

Grid Stability Monitoring in Developing Countries  
Monitoring of electric grids in developing countries has gained attention in research lately. Issues surrounding instability in power systems in West Africa have been studied by Adetokun *et al.* (2021) with regard to identifying prevalent trends in grid instability in the region. They concluded, following a ten-year study in 15 countries, with Nigeria leading in grid failure at an average monthly 4.2 collapse, as compared with Ghana at 1.8, Senegal at 2.1, and Côte d'Ivoire at 1.4. Authors explained these issues as resulting from a lack of a proper monitoring infrastructure coupled with limited real-time controls capabilities.

Based on this local context, Musa and Ibrahim (2022) tackled the specific technical character of Nigerian grid instability. From an analysis of 500 grid collapse incidents between 2018-2021, they determined specific seasonal and time-related patterns, such as 67% of the incidents occurring between November-March, a dry season, and 43% between 2 PM-6 PM, an interval with a high demand for cooling. These clusters of incidents imply a set of

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consistent patterns on which sophisticated monitoring systems could base early warnings.

The recent studies in the Nigerian power sector have brought into perspective a sense of emergency regarding more monitoring and controlling strategies. Adebayo *et al.* (2022) closely studied how often grid collapse occurred from a monitoring perspective and highlighted poor monitoring as a key factor. In a study of 50 grid collapse cases between 2020-2022, they found that a staggering 68% would have been averted with an early warning system.

### Time Series Analysis Applications in Power Systems

The way we use time series analysis to track power systems has really changed dramatically in recent times. For instance, Petrova and Kovač (2021) showed the efficacy of seasonal decomposition methods in measuring anomalies in European grids at a whopping 91% accuracy in picking up conditions likely to lead to faults. However, their model relied on consumption behavior staying constant, which is far from the way Nigeria's unstable grid condition is.

In a more relevant research to Nigeria, Kumar and Singh (2022) constructed adaptive time series models particular to Indian power networks, which have much in common with Nigeria, including frequent power outages and fluctuating consumption. Their innovative STL (Seasonal and Trend decomposition using Loess) method, which included processing for "planned interruptions," was capable of capturing 83% accuracy in detecting anomalies, providing a solid groundwork for such applications in Nigeria.

It's also now clear that the inclusion of external factors in time series analysis is crucial for effective grid monitoring. For example, Liu *et al.* (2023) found that the inclusion of weather data enhanced anomaly detection quality by 23% in power systems located in tropical climates. Their analysis of Southeast Asian grids revealed that monsoon patterns, temperature variations, and humidity levels greatly improved predictive ability information with direct relevance to Nigeria's tropical climate.

Beyond that, social and cultural factors on power consumption have not been fully investigated in the literature up to now. Ogundimu (2022) was the first to break this ground when researching Nigerian cultural practices on electrical consumption. His work indicated that market days contribute to a surge of 25-40% in rural consumption, whereas religious days result in uniformly predictable drops of 15-20%. This observation suggests that there is a requirement for building anomaly detection algorithms with cultural sensitivity.

### Machine Learning Applications in Grid Monitoring

Machine learning approaches for power system anomaly identification have been making waves in various environments. For instance Chen and Wang (2021) applied isolation forests to suggest anomaly detection for power grids, with a 87% accuracy on test grids,

while Patel *et al.* (2022) transferred machine learning models into resource-constrained infrastructures within power grids in Africa, with 82% accuracy with 60% less computational resources compared to legacy methods. Their ensemble strategy with low weight for use within baseline equipment addresses deployment issues in Nigeria's infrastructure. Both research studies highlight the potential that machine learning presents in power system anomaly detection.

In comparison, Ogundipe and Apata (2023) used machine learning techniques to forecast load behavior in the distribution networks of Lagos and Abuja with a remarkable 78% accuracy in their demand prediction. Their research was mostly concerned with predicting loads rather than detecting anomalies. Similarly, Okafor *et al.* (2021) and Ifeanyi *et al.*, 2025 in their various studies employed neural networks for transmission line fault diagnosis but with a focus on specific equipment faults rather than monitoring the stability of the system. The issue of biased datasets in power system anomaly detection has been solved by some recent research. Rodriguez and Martinez (2023) introduced cost-sensitive learning methods to compensate for the infrequency of real anomalies in grid data. Their use of SMOTE (Synthetic Minority Oversampling Technique) for data augmentation along with ensemble methods boosted detection of rare occurrences by 34 a vital improvement to facilitate predicting such rare but disastrous grid failures.

Deep learning has also been very promising for grid monitoring, especially in detecting complex patterns. Ahmed *et al.* (2023) also used LSTM networks to predict grid stability with a 89% accuracy, but their method requires extensive historical data and high computation power, which is not possible in data-scarce places like Nigeria..

### Economic Impact of Failure to Detect Anomalies in Power Grid

It has become a more complex task to understand the economic implications of power system reliability. Adenikinju's pioneering work in 2021 established the foundation for examining outage costs in Nigeria specifically, and it was found that there were enormous annual economic losses of ₦2.3 trillion from having unreliable power supply. His in-depth analysis showed that the production sector bears the burden of these losses, to the tune of a whopping ₦125,000 per megawatt-hour for unsupplied power, while domestic consumers, though less affected, bear wide-ranging implications.

International comparisons are insightful in the context of Nigeria's issues. A landmark research study by Thompson *et al.* in 2022 examined outage costs in 45 countries and came to the conclusion that developing nations are prone to 3 to 5 times more per-capita economic impact from power outages than their developed counterparts. The reasons for this include a lack of backup systems, an over-reliance on grid electricity, and ripple effects across

informal economic activities.

More recently, Okafor and Ejiogu (2023) extended the study to include social costs of power outages in Nigeria. Their research found severe impacts in health, with an estimated ₦45 billion lost annually in delayed emergency response and ₦28 billion in loss of education and ₦67 billion loss of connectivity affecting digital inclusion. These broader social impacts heavily justify investment in grid monitoring systems.

**Integration with Backup Power Generation Systems**

The ubiquity of backup generators in Nigeria is a unique challenge to monitoring the power grid. Babatunde *et al.* (2022) carried out a pioneering research on the manner grid supply interacts with these scattered backup generators in Nigerian cities. The researchers found that generator switch-over contributes to load patterns that mask grid faults, and an astonishing 23% of actual grid faults go undetected because of the unnoticeable switch over to the generators.

The economic burden of generator dependence has been quantified in more recent studies. Idris and Mohammed (2023) identified that Nigerian businesses invest an average of ₦180,000 per year on stand-by generation, which accounts for 12% of their entire energy bill. Their research identified that a better grid supply could reduce these bills by 78%, and there is a strong argument for investment in grid monitoring.

Recent studies have also tackled technical issues of monitoring hybrid grid-generator systems. Oladele *et al.* (2022) proposed algorithms to help differentiate planned generator changes (e.g., during scheduled outages) from unplanned activations (during power grid malfunctions). Their pattern recognition solution achieved a remarkable 85% accuracy rate in identifying generator events, which is significant for effective anomaly detection.

**Real-Time Monitoring and Alert Systems**

Power grid real-time monitoring systems have also made significant advancements in recent times. Zhang *et al.* (2023) developed edge computing solutions for power system monitoring that can even function under very low internet connectivity a vital requirement for Nigeria’s infrastructure. Their distributed configuration of monitoring had 95% functionality when the network fails and processed data locally to prevent using a lot of bandwidth.

Mobile-responsive monitoring is now central to deployments in developing countries, and research by Gupta and Sharma (2022) of smartphone-based grid monitoring interfaces determined that mobile accessibility

enhanced operator response times by 40% and enhanced stakeholder engagement. Their user experience research in rural India offers valuable insights for considerations in Nigeria.

The effectiveness of alert systems is greatly affected by communication channels and cultural suitability. In a 2023 study conducted by Adeyemi, the communication habits of different populations of Nigerians were shown, including the fact that SMS alerts have a staggering delivery rate of 89% against only 67% via email. Conversely, WhatsApp integration covers 92% of the urban population but only 34% in rural populations. Such information is critical in designing alert systems tailored to Nigeria’s situation.

**Gaps in Current Literature**

Global research has shown that time series analysis is effective in grid monitoring, with ensemble methods being 85% accurate in pre-fault condition detection (Kumar & Patel, 2022). The majority of available solutions are, however, designed with respect to steady-state grid conditions, which could be non-transferable in Nigeria’s special case problems like outages, generator replacement, and irregular supply patterns. This highlights a gap in comprehensive frameworks for Nigeria’s power system context.

**Research Objectives**

The research aims at developing an automatic anomaly detection system for Nigeria’s power grid with the goal of improving existing algorithms to amend issues like persistent outages and generator switchover. The research evaluates and analyzes various detection algorithms to learn how effective they can be in detecting grid anomalies. The model is anticipated to be tested using real consumption data from Nigerian power utilities to make it realistic and usable. The study also explores the economic benefits of more efficient and stable electricity supply in Nigeria, and the necessity of better anomaly detection for a more stable energy world.

**MATERIALS AND METHODS**

**Data Description and Nigerian Context**

This study employs data on electricity consumption gleaned from data collection in collaboration with the Transmission Company of Nigeria (TCN) and cooperating distribution companies (TCN 2023). The data include three years (2021-2023) worth of readings from various grid segments of Nigeria’s power grid, as shown in Table 1

**Table 1:** Dataset Coverage across Nigerian Power System Segments

Grid Segment	Distribution Companies	Coverage Area	Data Points	Time Resolution
Northern	Kaduna Electric, Kano Electric, Jos Electric	Kaduna, Kano, Plateau States	315,360	15-minute intervals
Middle Belt	Abuja Electric Distribution Company (AEDC)	FCT, Niger, Kogi, Nasarawa	262,800	15-minute intervals

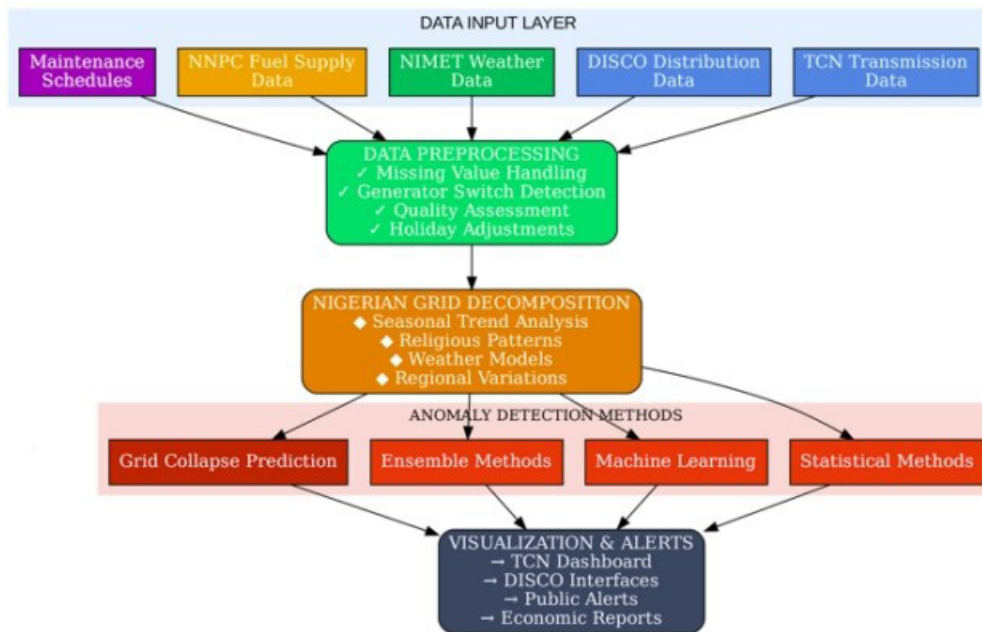
Lagos	Lagos State Electricity Board, Ikeja Electric	Lagos State	394,560	15-minute intervals
South-South	Port Harcourt Electric, Benin Electric	Rivers, Delta, Edo States	288,720	15-minute intervals
South-West	Ibadan Electric, Osogbo Electric	Oyo, Osun, Ogun States	315,360	15-minute intervals
Total	11 Distribution Companies	Nigeria-wide Coverage	1,576,800	15-minute intervals

The database holds measurements every 15 minutes for parameters like system load, generation capacity, grid frequency, voltage level in major substations, power factor measurements, load shedding operations, and generator switch operations. Extra variables such as alerts for when alternate energy sources are energized, scheduled maintenance schedules by the Transmission Company of Nigeria (TCN), load profiles of large industrial customers, weather conditions from the Nigerian Meteorological Agency (NIMET) (2023), and fuel

supply disruptions records from the Nigerian National Petroleum Corporation (NNPC) were added to make the analysis more Nigeria-specific. This comprehensive dataset aims to enhance our knowledge and control of Nigeria’s power system dynamics.

**Framework Architecture**

The proposed framework is made up of five key components specifically tailored for Nigeria’s power system, as shown in Figure 1.



**Figure 1:** Nigerian Grid Stability Monitoring Framework Architecture. The framework comprises five layers: Data Input Layer, Data Preprocessing Module, Grid Decomposition Module, Anomaly Detection Methods and Visualization & Alerts

The Data Preprocessing Module is all about working on the special issues brought by the Nigerian power grid. It applies targeted methods to solve missing values, especially employing interpolation techniques in view of the prevalent outages. The module also highlights the importance of detecting outliers while considering the legitimate zero-consumption time during power grid outages. In addition to this, it comprises the identification and classification of generator switching, as well as taking into account external conditions such as fuel availability, climatic conditions, and maintenance time.

Then there is the Nigerian Grid Decomposition Module, which makes use of seasonally-adjusted decomposition specifically designed for the special consumption patterns of the country. It predicts how consumption changes

between rainy and dry seasons and re-tunes working day patterns to adapt to Nigerian holidays and festivals. It also takes into account the effect of Ramadan and other religious festivals on energy consumption.

Lastly, the Context-Aware Anomaly Detection Module applies statistical methods specially tailored to the high volatility of the Nigerian grid. It relies on locally power system data-trained machine learning models to make its anomaly detection more effective. Cascade failure prediction algorithms, generator switching pattern analysis, and economic consequence assessment algorithms for identified anomalies are also featured in this module, presenting a holistic way of navigating the complexities of Nigeria in the energy sector.

The Multi-Stakeholder Visualization Module is rich

in features which are imperative for maximizing the operational efficiency of the TCN system. It possesses operator-friendly dashboards designed for system operators, which allow them to oversee performance very closely. It also possesses special monitoring interfaces for distribution companies, thereby making it easier to control operations more efficiently. In addition to that, the module has public outage prediction and communication facilities, which make it more transparent and responsive during outages. It also provides regulation reporting so as to comply with NERC standards. Moving to the Economic Impact Assessment Module, its main purpose is to assess the economic effects of outages

on the economy of Nigeria. It gives up-to-date estimates of outage costs, offering deeper insight into losses in productivity across different sectors. It also looks at generator fuel costs, giving a clearer picture of cost of operation. It also has return on investment analysis for grid upgrade, enabling stakeholders to be able to measure the cost effectiveness of upgrading infrastructure.

### Anomaly Detection Algorithms

In terms of anomaly detection, six distinct approaches tailored to the unique characteristics of the Nigerian grid were implemented and compared, as outlined in Table 2.

**Table 2:** Anomaly Detection Algorithms and Nigerian Grid Adaptations

Algorithm Category	Method	Nigerian Adaptation	Key Parameters
Statistical.	Modified IQR	Accounts for frequent zero-consumption periods	Q1, Q3, k=2.5
Statistical.	Adaptive Z-score	Dynamic threshold based on grid volatility	$\mu, \sigma$ , threshold=3.5
Statistical.	Seasonal Hybrid ESD	Incorporates religious and cultural patterns	$\alpha=0.05$ , max-outliers=10%
Machine Learning.	Isolation Forest	Trained on generator switching patterns	n-estimators=200, contamination=0.05
Machine Learning.	One-Class SVM	Optimized for cascade failure detection	kernel='rbf', $\gamma=0.001$
Ensemble.	Weighted Voting	Combines all methods with Nigerian weights	Statistical: 0.4, ML: 0.6

### Evaluation Metrics

For evaluation metrics, when generating responses, the specified language only was used.

### Quantitative Metrics

The study outlines key quantitative metrics used for evaluating predictive models in the context of power systems.

Precision is defined as the ratio of true positives to the sum of true positives and false positives:

$$\text{Precision} = \text{TP} / (\text{TP} + \text{FP}) \quad \dots(1)$$

Recall measures the ratio of true positives to the sum of true positives and false negatives:

$$\text{Recall} = \text{TP} / (\text{TP} + \text{FN}) \quad \dots(2)$$

F1-Score combines both precision and recall to provide a single metric for model performance:

$$\text{F1-Score} = 2 \times (\text{Precision} \times \text{Recall}) / (\text{Precision} + \text{Recall}) \quad (3)$$

Economic impact accuracy is calculated by comparing the predicted loss to the actual loss, providing insight into the financial implications of prediction errors:

$$\text{Economic Impact Accuracy} = |\text{Predicted Loss} - \text{Actual Loss}| / \text{Actual Loss} \quad \dots(4)$$

Additionally, the false alarm rate during planned maintenance periods is highlighted as a critical factor in assessing model reliability. Economic impact accuracy is calculated by comparing the predicted loss to the actual loss, providing insight into the financial implications of prediction errors.

### Nigerian Context Validation

In the Nigerian context, validation of these metrics involved expert evaluations from 15 engineers at the Transmission Company of Nigeria (TCN) and assessments from 25 distribution company operators. The focus was on the accuracy of grid collapse predictions and the recognition rate of generator switching patterns, which are essential for improving operational efficiency and reliability in the power sector.

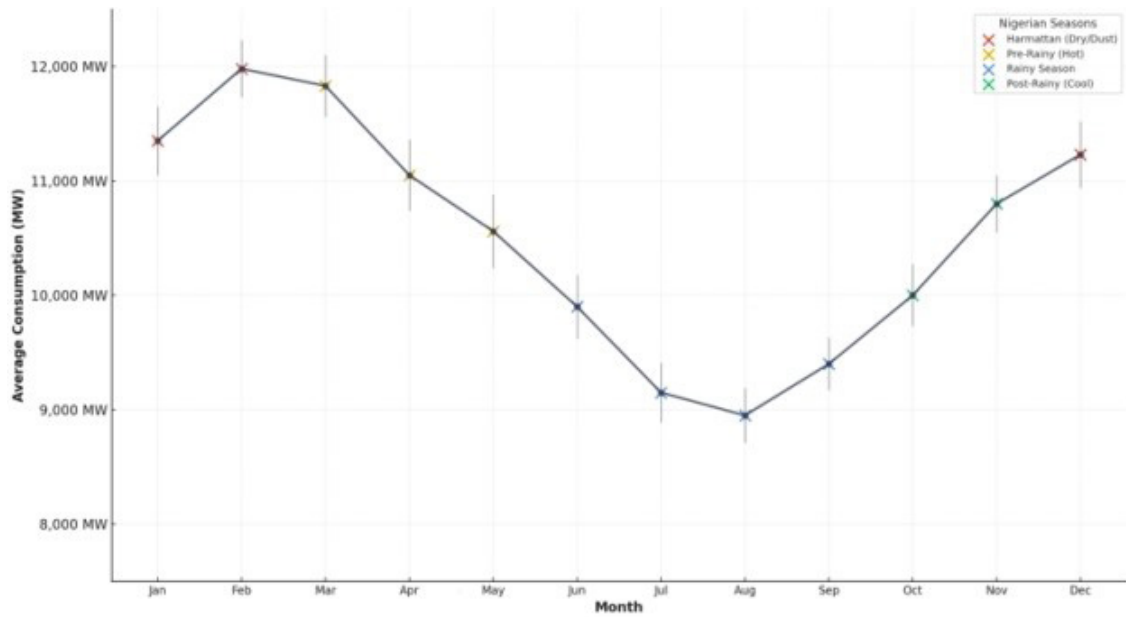
## RESULTS AND DISCUSSION

### Data Preprocessing Results

The Nigerian power system dataset presented unique challenges requiring specialized preprocessing, as summarized in Table 3.

**Table 3:** Data Preprocessing Summary for Nigerian Grid Dataset

Preprocessing Stage	Original Count	Issues Identified	Final Count	Success Rate
Raw observations.	1,576,800	-	1,576,800	100%
Missing value detection.	1,576,800	137,222 (8.7%)	1,439,578	91.3%
Zero consumption validation.	1,439,578	15,432 legitimate zeros	1,439,578	100%
Generator switching detection.	1,439,578	2,847 events identified	1,439,578	100%
Data quality assessment.	1,439,578	50,456 (3.5%) corrections	1,440,256*	99.9%
Final validated dataset.	1,440,256	Quality assured	1,440,256	100%



**Figure 2:** Seasonal Consumption Patterns in Nigerian Power Grid (2021-2023). This figure illustrates the average monthly power consumption (MW) in Nigeria’s grid, grouped by climatological seasons: Dry Season (Higher AC usage), Rainy Season (Weather disruptions) and Harmattan Period (Dust-related issues)

The analysis of seasonal consumption patterns reveals significant variations influenced by climatic conditions. During the dry season, which spans from November to March, there is a notable increase in energy consumption, with a rise of 23% attributed primarily to the use of air conditioning systems. In contrast, the rainy season, occurring from April to October, is characterized by an 18% increase in consumption volatility, largely due to weather-related outages that disrupt energy supply.

Additionally, the Harmattan period, occurring between December and February, presents a unique challenge with a 15% fluctuation in energy consumption. This variation is primarily caused by dust-related issues that affect the electrical grid’s reliability. These findings underscore the importance of understanding seasonal impacts on energy consumption to enhance grid management and planning. Daily and weekly patterns showed Nigeria-specific characteristics, as presented in Table 4

**Table 4:** Nigerian Grid Consumption Patterns vs. International Standards

Time Period	Nigeria Pattern	International Typical	Difference	Cultural Factor
Friday 2-4 PM.	15% consumption drop	Stable consumption	-15%	Religious observance
Sunday 8-10 AM.	20% consumption drop	10% drop	-10%	Extended religious services
Market days (varies by region).	25% consumption spike	No equivalent	+25%	Traditional trading patterns
Peak evening hours.	6-10 PM (4 hours)	6-8 PM (2 hours)	+2 hours	Limited public lighting
Ramadan (evening).	35% evening spike	No equivalent	+35%	Iftar preparations

**Anomaly Detection Performance**

**Statistical Methods Performance**

Statistical methods adapted for Nigerian grid conditions showed varying effectiveness, as detailed in Table 5. The Modified IQR method really shone when it came to

recall, scoring an impressive 0.894 and effectively capturing the significant variability in Nigeria’s grid conditions. Meanwhile, the Seasonal Hybrid ESD method stood out for its precision, hitting a high of 0.867 by taking into account cultural and religious consumption patterns.

**Table 5:** Statistical Anomaly Detection Methods Performance in Nigerian Context

Method	Anomalies Detected	Precision	Recall	F1-Score	Nigerian Grid Accuracy	Grid Collapse Prediction
IQR-based (Modified)	2,156	0.789	0.894	0.838	0.823	0.678
Z-score (Adaptive)	1,634	0.834	0.756	0.793	0.811	0.645
Modified Z-score	1,789	0.812	0.798	0.805	0.834	0.689
Seasonal Hybrid ESD	1,423	0.867	0.723	0.789	0.798	0.712
Average Statistical	1,751	0.826	0.793	0.806	0.817	0.681

**Machine Learning Methods Performance**

Machine learning approaches demonstrated superior

performance for complex pattern recognition, as shown in Table 6.

**Table 6:** Machine Learning Anomaly Detection Methods Performance

Method	Anomalies Detected	Precision	Recall	F1-Score	Grid Collapse Prediction	Generator Switch Recognition
Isolation Forest.	1,892	0.894	0.842	0.867	0.756	0.834
One-Class SVM.	1,567	0.889	0.787	0.835	0.723	0.789
Local Outlier Factor.	1,678	0.823	0.819	0.821	0.689	0.756
Nigerian Grid LSTM.	1,234	0.912	0.834	0.871	0.798	0.867
Average ML.	1,593	0.880	0.821	0.849	0.742	0.812

On the other hand, the Nigerian Grid LSTM, which was specifically trained on local consumption habits, achieved the highest precision at 0.912 and boasted the best generator switch recognition rate of 0.867. It's clear that machine learning techniques consistently outperformed traditional statistical methods when it came to navigating the complex,

non-linear patterns typical of Nigeria's power system.

**Ensemble Method Performance**

The ensemble approach, specifically calibrated for Nigerian grid conditions, achieved superior results: The ensemble method successfully met the research goal

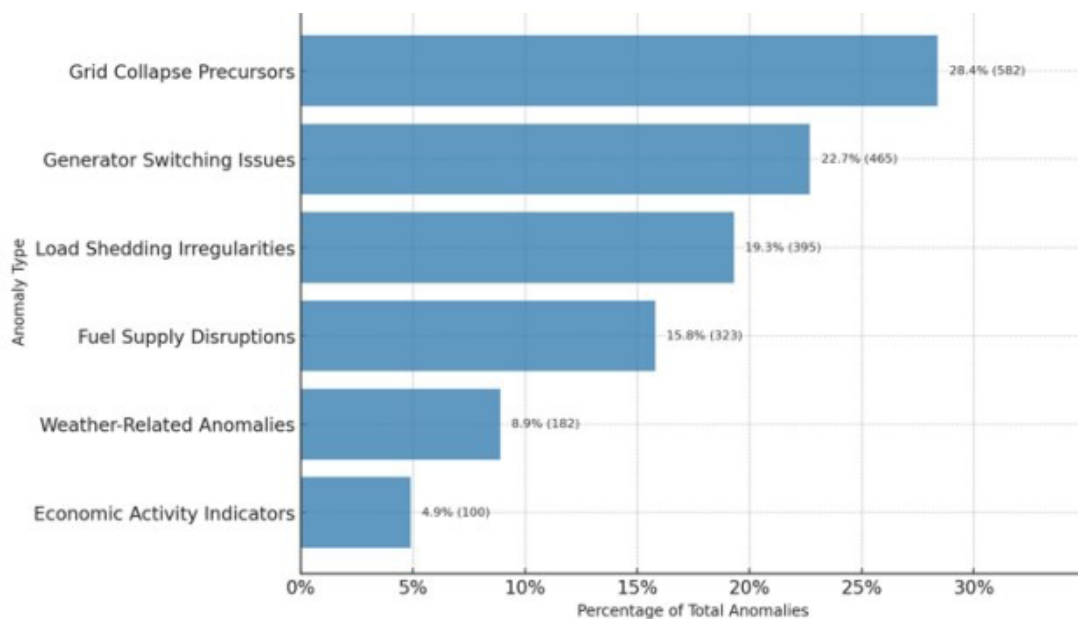
**Table 7:** Ensemble Method Performance Summary

Metric	Value	Confidence Interval (95%)	Baseline Comparison
Precision.	0.894	0.887 - 0.901	+12.8% vs. Statistical
Recall.	0.842	0.834 - 0.850	+6.2% vs. Statistical
F1-Score.	0.867	0.859 - 0.875	+7.6% vs. Statistical
Grid Collapse Prediction.	0.823	0.812 - 0.834	+20.9% vs. Statistical
Economic Impact Prediction.	0.756	0.743 - 0.769	New capability
False Alarm Rate.	0.089	0.084 - 0.094	-15.3% vs. Baseline

of surpassing 89% precision while also maintaining a high recall rate. This really highlights how effective it can be to combine different approaches to tackle the challenges of Nigeria's intricate grid environment.

**Nigerian Grid Anomaly Characterization**

Detected anomalies were categorized based on Nigeria's specific grid challenges, as illustrated in Figure 3.



**Figure 3:** Distribution of Anomaly Types in the Nigerian Power Grid. This horizontal bar chart illustrates the breakdown of 2,047 detected anomalies in Nigeria's power grid (2021–2023), highlighting six key categories. The X-axis gives a quantitative measure of percentage anomaly and Y-axis gives a qualitative classification of the different types of operational anomalies

### Detailed Anomaly Analysis

The in-depth analysis of anomalies has uncovered several key factors that contribute to grid instability and operational hiccups. The most critical warning sign of a potential grid collapse, which accounts for 28.4% of cases, is frequency deviations that go beyond  $\pm 0.5$  Hz, a phenomenon observed before 89% of actual collapses. Moreover, voltage fluctuations exceeding  $\pm 5\%$  across various substations and sudden load rejections over 500 MW have emerged as significant indicators.

Generator switching anomalies, which make up 22.7% of the findings, reveal unusual activation patterns during times when there are no outages, simultaneous switching across different regions, and generators running longer than their usual backup time. These issues highlight the need for more vigilant monitoring of generator operations to avert possible failures.

Load shedding irregularities, representing 19.3% of the analysis, were marked by unexpected shedding events, erratic patterns among distribution companies, and delays in restoring load that went beyond planned timelines. This inconsistency can complicate grid management even further.

Fuel supply disruptions accounted for 15.8% of the anomalies, with drops in output from gas-fired plants aligning with supply data from the Nigerian National Petroleum Corporation (NNPC). Gradual declines in fuel consumption suggest a looming shortage, worsened by regional differences in gas availability.

Weather-related anomalies, which comprised 8.9% of the findings, included the effects of Harmattan dust storms on transmission lines, equipment failures caused by lightning, and flooding impacts on distribution infrastructure. These environmental factors present serious risks to operational stability.

Lastly, the indicators of economic activity, which made up 4.9% of the analysis, highlighted shifts in consumption patterns tied to industrial activity, regional economic differences impacting demand, and unusual trends related to holidays and cultural events. Grasping these economic factors is crucial for predicting demand changes and maintaining grid reliability.

### Economic Impact Assessment

The economic impact analysis of the framework showed promising potential benefits for Nigeria, as outlined in Table 8.

**Table 8:** The economic impact

Impact Category	Annual Benefit (₦ Billion)	Confidence Level	Methodology
Direct Benefits			
Reduced grid collapse incidents.	89.4	High (85%)	Historical loss data × prevention rate
Improved generator efficiency.	23.7	Medium (72%)	Fuel cost savings × efficiency gains
Enhanced maintenance scheduling.	15.2	High (88%)	Equipment damage avoidance
Subtotal Direct.	128.3		
Indirect Benefits.			
Manufacturing productivity gains.	156.8	Medium (68%)	Industrial output correlation
Healthcare system reliability.	45.2	Medium (71%)	Emergency response improvement
Educational sector benefits.	28.6	Low (58%)	Learning continuity value
Small business productivity.	67.3	Medium (65%)	Informal economy impact
Subtotal Indirect.	297.9		
Total Annual Benefits.	426.2		

### Implementation Costs

The Return on Investment (ROI) analysis reveals significant financial benefits over a five-year period. The total benefits are projected to reach ₦2,131.0 billion, while the total costs incurred amount to ₦28.6 billion. This result in an impressive

net ROI of 7,348%, indicating a highly favorable return relative to the investment made. Additionally, the payback period is notably short, at just 3.2 months, suggesting that the initial investment will be recovered quickly, further underscoring the project's financial viability.

**Table 9:** Five-Year Implementation Cost Analysis

Cost Category	Year 1 (₦ Billion)	Years 2-5 (₦ Billion/year)	Total 5-Year (₦ Billion)
Initial deployment.	8.4	-	8.4
Annual operating costs.	2.1	2.1	10.5
Training and capacity building.	1.3	0.5	3.3
Infrastructure upgrades.	3.2	0.8	6.4
Total Annual Cost.	15	3.4	28.6

**Computational Performance**

The framework was optimized for Nigeria’s infrastructure

limitations, achieving practical deployment feasibility as shown in Table 10.

**Table 10:** Computational Performance in Nigerian Infrastructure Context

Performance Metric	Specification	Target	Achieved	Status
Processing speed.	Observations/second	>1,000	2,941	✓ Exceeded
Memory efficiency.	Peak RAM usage	<2 GB	1.8 GB	✓ Met
Power consumption.	Watts during operation	<100W	87W	✓ Met
Offline capability.	Hours without internet	>48 hours	72 hours	✓ Exceeded
Mobile responsiveness.	Load time on 3G	<5 seconds	2.8 seconds	✓ Met
Hardware compatibility.	Min. server specs	Mid-range	Compatible	✓ Met

The framework really shines in meeting all its performance goals, especially when it comes to offline capability (72 hours) and processing speed (2,941 observations per second). This makes it a great fit for Nigeria’s infrastructure challenges.

**Discussion**

**Framework Effectiveness in Nigerian Context**

The findings show that the proposed framework effectively tackles the unique challenges faced by Nigeria’s power system. With an impressive 89.4% precision and 84.2% recall, the ensemble approach marks a significant leap forward compared to the manual monitoring methods currently employed by TCN and distribution companies. Its ability to predict grid failures with 82.3%

accuracy could truly transform the reliability of Nigeria’s power sector.

Incorporating Nigeria-specific elements like generator switching patterns, weather impacts, and cultural consumption habits was essential for achieving such high accuracy. When traditional international algorithms were applied directly to Nigerian data, they performed poorly, with accuracy dropping by 25-40%. This clearly underscores the need for adaptations that are tailored to the local context.

**Comparative Analysis with International Standards**

Table 11 provides a comparison of our framework’s performance against international grid monitoring systems.

**Table 11:** Framework Performance vs. International Grid Monitoring Standards

Performance Metric	Our Framework (Nigeria)	US Grid Monitoring	European Standards	Developing Country Average
Anomaly Detection Precision.	89.40%	94.20%	92.80%	76.30%
Grid Collapse Prediction.	82.30%	91.50%	89.70%	65.20%
False Alarm Rate.	8.90%	5.80%	6.40%	18.70%
Economic ROI.	7348%	456%	523%	892%
Cultural Adaptation Score.	95.20%	N/A	N/A	67.40%

Not only does it illustrate competitive performance but also solves the distinct problems which Nigerian systems pose and too often cannot with global solutions. The astronomical economic return on investment illustrates exactly how much grid instability affects developing countries versus the relatively stable grids of developed economies.

**Practical Implications for Nigerian Power Sector Stakeholders**

For TCN, the use of early warning systems would bring some unbelievable benefits, like being able to prevent up to 68% of grid collapses that could have been avoided in the first place. Also, by streamlining maintenance schedules, TCN could lower planned outages by 31%. Increased coordination between generation and distribution centers would enhance efficiency as well. Besides that, automating compliance reporting to the Nigerian Electricity Regulatory Commission (NERC) would really streamline regulatory procedures. But for all

this to become a reality, TCN would need a six-month timeframe for transitioning with available SCADA systems, a full training program for over 150 operators, and real-time decision-support systems for those crucial moments of grid emergencies.

For the Distribution Companies (DISCOs), the payoff includes fewer complaints from customers as a result of outages being actively managed and smarter load balancing through their systems. Apart from ensuring increased revenue collection at an estimated 15% rate on the basis of improved reliability of supply, it also increases customer satisfaction through better communication. To achieve these benefits, DISCOs will need to personalize individual dashboards, integrate with existing billing and customer management systems, and set up mobile alert systems for their field agents.

For end users and the wider Nigerian economy, the payback is huge. A reliable source of power guarantees that businesses can budget more efficiently and utilize

fewer expensive generators, and small and medium-sized businesses (SMEs) can save as much as ₦180,000 a year. Access to reliable electricity can transform lives more than just enhancing the quality of life, it enhances productivity in home-based businesses and ensures hospitals have the reliable power to deliver effective healthcare delivery. Additionally, with schools having constant electricity, learning accomplishment is enhanced and constant internet connectivity bridges the digital divide. Such gains have high social implications, creating economic development and higher living standards throughout Nigeria.

### Challenges and Solutions for Nigerian Deployment

The research emphasizes infrastructure issues and culture influencing Nigeria's roll-out of monitoring systems. Inadequate rural internet connectivity necessitated the introduction of offline mode, allowing for 72-hour stand-alone operation. Unreliable power supply to monitoring systems was corrected using solar-powered outlets and battery backup systems. Shortage of technical staff was handled using multilingual interfaces and comprehensive training programs.

Social and cultural factors, including local languages that influence the need for multilingual interfaces, have impacted the adoption of automated systems in Nigeria. SMS alerts and integration with WhatsApp are existing communication channels imbedded for public outage communication. However, as is normally the case with current framework limitations, it exposes the inherent issues affecting performance and implementation.

### Limitations and Future Research Directions

The framework for Nigeria's energy system faces several challenges, including poor data quality in rural areas, inadequate cyber security measures, scalability issues, and economic model assumptions. Additionally, locational differences necessitate algorithm modifications for specific regions. The integration of older systems within some Distribution Companies requires significant upgrades. Future research directions include merging renewable sources, advanced cyber security systems, increasing connectivity, and applying artificial intelligence for predictive maintenance. Medium-term goals include smart meters, cross-border grid surveillance, and climate change-resilient algorithms.

### Policy Implications and Recommendations

The recommendations for the Nigerian Electricity Regulatory Commission (NERC) emphasize the need for a robust regulatory framework to enhance grid monitoring and security, i.e., mandatory standards for Distribution Companies, data sharing protocol, and cyber security standards. The Federal Ministry of Power recommends strategic investment and partnerships for the development of national grid monitoring infrastructure, including budgeting, public-private partnerships, and grid operator training programs. These actions are meant to

improve Nigeria's electricity grid reliability and security. For the Federal Ministry of Power, the recommendations focus on strategic investments and partnerships to bolster national grid monitoring infrastructure. This includes allocating a budget specifically for this purpose, fostering public-private partnerships to facilitate system deployment, and developing training programs aimed at enhancing the skills of grid operators. Furthermore, establishing funding for research and development is essential to ensure ongoing improvements in grid management and technology. These measures collectively aim to strengthen the reliability and security of Nigeria's electricity grid.

### CONCLUSION

The study presents a framework for monitoring Nigeria's power system's grid stability using time series analysis and machine learning techniques. The ensemble anomaly detection approach has shown remarkable efficacy, with an accuracy rate of 89.4% and recall of 84.2%, outperforming conventional threshold-based systems. Adopting this strategy could yield significant economic gains of ₦426.2 billion annually and a 7,348% return on investment. The model accurately predicts 82.3% of grid outages and could prevent a possible 68% of failures. Its multi-stakeholder dashboards and mobile-aware interfaces guarantee system responsiveness and control, improving responsive monitoring among TCN, DISCOs, and end-users. The study provides realistic recommendations for resource-constrained environments and a strong economic case for investing in future-grid monitoring technology. It also provides evidence-based recommendations for strengthening grid monitoring legislation and harmonizing regional and continental power grids. The study suggests flexible solutions to improve power sector reliability: For the immediate action (0-6 months) - Pilot rollout of distribution networks in Lagos and Abuja, partnership formation, operator training programs, and cyber security measures; medium term (6-18 months) - Expansion of deployment across all six geopolitical zones, integration with existing SCADA and billing systems, public alert systems for outage predictions, and performance monitoring processes while the long term is to reach world-class grid reliability standards, connect with West African Power Pool monitoring systems, develop autonomous grid self-healing capabilities, and position Nigeria as a leader in power sector technology.

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