International Journal of Electrical, Electronics & Communication Engineering (IJEECE)
DOI: 10.5281/zenodo.17088219

Research Article

Leveraging Power Quality Index (PQI) for Enhanced Energy Management and QoS

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Cite as:
Anyahara, I. C., and Onoh, G. N. (2025). Leveraging Power Quality Index (PQI) for Enhanced Energy Management and QoS. *International Journal of Electrical, Electronics & Communication Engineering, 6(2), 26-40.* *https://doi.org/10.5281/zenodo.17088219*

Abstract

In many emerging markets, unreliable grid power poses a significant challenge to the operational efficiency of telecom infrastructure. This paper examines how tower companies can leverage the Power Quality Index (PQI) to transition from a basic availability-focused model to a more comprehensive, quality-driven energy management approach. Using field data from smart meters and IoT sensors across multiple telecom sites, a composite PQI model is developed, incorporating key parameters such as voltage stability, frequency consistency, harmonic distortion, and load utilization. These metrics are normalized and visualized through a centralized dashboard, enabling real-time monitoring, predictive maintenance, and improved SLA compliance. The analysis reveals strong correlations between PQI scores and normalized site performance indicators—including AC voltage, AC load utilization, frequency, RPM, DC voltage, and DC load utilization—which collectively inform the site's PQI score. Sites with high PQI scores exhibit greater power reliability and operational efficiency, while low-scoring sites show signs of instability and inefficiency. The findings support the adoption of PQI frameworks as a strategic tool for enhancing service quality, reducing operational costs, and guiding infrastructure investments in telecom networks.

Keywords: Power Quality Index (PQI); Enhanced Energy Management; QoS

Introduction

Mobile Network Operators (MNOs) increasingly rely on tower companies to manage passive infrastructure, especially power systems, to reduce capital expenditure and improve operational efficiency. In regions with unstable grid supply, power disruptions—like voltage fluctuations and outages—can degrade network performance and raise operational costs, directly affecting Quality of Service (QoS) (Asentria, 2019; Milanović, Abdelrahman, & Liao, 2018).

To address these issues, tower companies use the Power Quality Index (PQI), a composite metric that evaluates power health through parameters such as voltage stability, frequency consistency, harmonic distortion, power factor, and transient events (Milanović et al., 2018). Tools like the Compound Bus PQ Index (CBPQI) offer a holistic view of power performance. International standards like IEC 61000 and IEEE 519 guide consistent measurement and benchmarking (Eureka, 2025; IEEE PES, 2025).

Telecom towers, especially in emerging markets, face challenges including unreliable grid supply, high costs, and equipment degradation. PQI supports automation and remote monitoring, enabling proactive maintenance and intelligent switching between power sources to optimize energy use (Asentria, 2019; Naderi, Abedi, & Gharehpetian, 2018). Integration with IoT platforms and compliance with IEC 62586-1 enhance operational agility (IEEE PES, 2025).

PQI insights help implement strategies like hybrid energy systems, smart controllers, and load balancing. Distributed generation technologies, such as inverter-based solar, support PQI by offering voltage regulation and harmonic filtering (Naderi et al., 2018). Such approaches enhance uptime while supporting sustainability objectives.

Cost optimization is a key benefit. PQI-driven management reduces fuel use, maintenance, and equipment wear, while improving SLA compliance. In Rwanda, PQI-based energy management cut operational costs by over 50% (Mihigo, 2016). Regulatory bodies like EACO promote such practices to enhance efficiency (EACO, 2021).

Case studies show PQI's impact: a tower firm in East Africa reduced generator runtime by 30% and improved uptime by 20% (Mihigo, 2016). In India, PQI integration with hybrid systems cut diesel use by 40% and improved SLA performance (Hill, Khanna, & Stecker, 2008).

Despite its benefits, PQI implementation faces hurdles like data accuracy, legacy systems, and training needs. A robust PQI framework requires technical investment and a culture of continuous improvement (MHC Oxford, 2025). Looking ahead, AI and cloud platforms are enhancing PQI with predictive analytics and centralized monitoring. Regulatory incentives are also emerging to support power quality upgrades (IEEE PES, 2025).

2. Literature Review

Power Quality Index (PQI) has emerged as a critical metric for evaluating the reliability and efficiency of electrical power systems, particularly in telecom infrastructure. Milanović et al. (2018) introduced the Compound Bus PQ Index (CBPQI), which aggregates multiple power quality phenomena—such as voltage sags, harmonics, and unbalance—into a single evaluative framework using an analytic hierarchy process. This approach enables a holistic assessment of power performance, which is essential for telecom sites that rely on stable power to maintain network uptime. Traditional PQI metrics have been in use for over two decades, but the evolution of power networks and the integration of distributed energy resources (DERs) have necessitated new indices and measurement techniques. Barros (2022) emphasized the need for updated PQI standards to address emerging disturbances such as rapid voltage changes, high-frequency distortions, and flicker emissions. These developments are particularly relevant for telecom towers powered by hybrid systems involving solar, battery, and grid sources.

Tower companies (TowerCos) have increasingly taken on the responsibility of managing power infrastructure for mobile network operators (MNOs). In emerging markets, this includes deploying energy service models such as T-ESCOs (TowerCo Energy Service Companies), which integrate power management into their core operations. These entities use PQI data to monitor uptime, optimize energy use, and reduce operational costs, especially in off-grid or unreliable grid environments. Energy optimization is a growing imperative for telecom operators. McKinsey (2025) reported that energy costs can account for up to 5% of telecom revenue, and that holistic strategies—including PQI-based monitoring—can reduce energy costs by 15–30%. Gupta (2025) further highlighted that PQI enables dynamic power provisioning, predictive maintenance, and efficient load balancing, all of which contribute to cost savings and environmental sustainability.

Quality of Service (QoS) in mobile networks is directly influenced by power reliability. Kora et al. (2013) proposed a unified approach to assess user satisfaction based on key performance indicators (KPIs), linking power quality to service delivery outcomes. PQI serves as a foundational metric that supports these KPIs by ensuring stable and efficient power supply to telecom equipment.

Modern PQI systems are increasingly integrated with IoT platforms and smart dashboards. These systems enable real-time anomaly detection, automated source switching, and SLA compliance reporting. Milanović et al. (2018) and Barros (2022) both advocate for the use of advanced PQI analytics to support decision-making and infrastructure planning.

To theoretically relate the different inputs of a Power Quality Index (PQI) composite dashboard, especially in scenarios where the load is not highly inductive, a multi-criteria mathematical modeling approach is often used. This involves combining several power quality parameters—such as voltage sag, harmonics, flicker, and unbalance—into a single composite index using weighted aggregation techniques.

Mathematical Relationship

One widely accepted method is the Analytic Hierarchy Process (AHP), which allows for the integration of multiple PQ parameters into a compound index. The general form of the composite PQI can be expressed as:

$$\mathbf{PQI_{composite}} = \sum_{i=1}^{n} w_i \,.\, PQ_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(1)}$$

Where:

- PQ_i is the normalized value of the i-th power quality parameter (e.g., THD, voltage sag, flicker).

- w_i is the weight assigned to the i-th parameter based on its relative importance.

- n is the total number of parameters considered.

Key Parameters in Low-Inductance Load Scenarios

When the load is not highly inductive, the displacement power factor (DPF) tends to be closer to unity, and harmonic distortion (especially current THD) becomes more relevant than reactive power. This shifts the emphasis of the PQI from reactive power-related metrics to distortion and voltage stability metrics.

Key Parameters

i. Total Harmonic Distortion (THD): Measures waveform distortion due to harmonics.
ii. Voltage Unbalance: Important in three-phase systems.
iii. Flicker Index: Relevant for loads sensitive to voltage fluctuations.
iv. True Power Factor (TPF): More accurate than DPF in non-linear load conditions.

Application

Milanović et al. (2018) proposed a Compound Bus PQ Index (CBPQI) using AHP to evaluate PQ at a bus level, considering voltage sag, harmonics, and voltage unbalance simultaneously. This method is particularly effective in distribution networks with mixed load types.

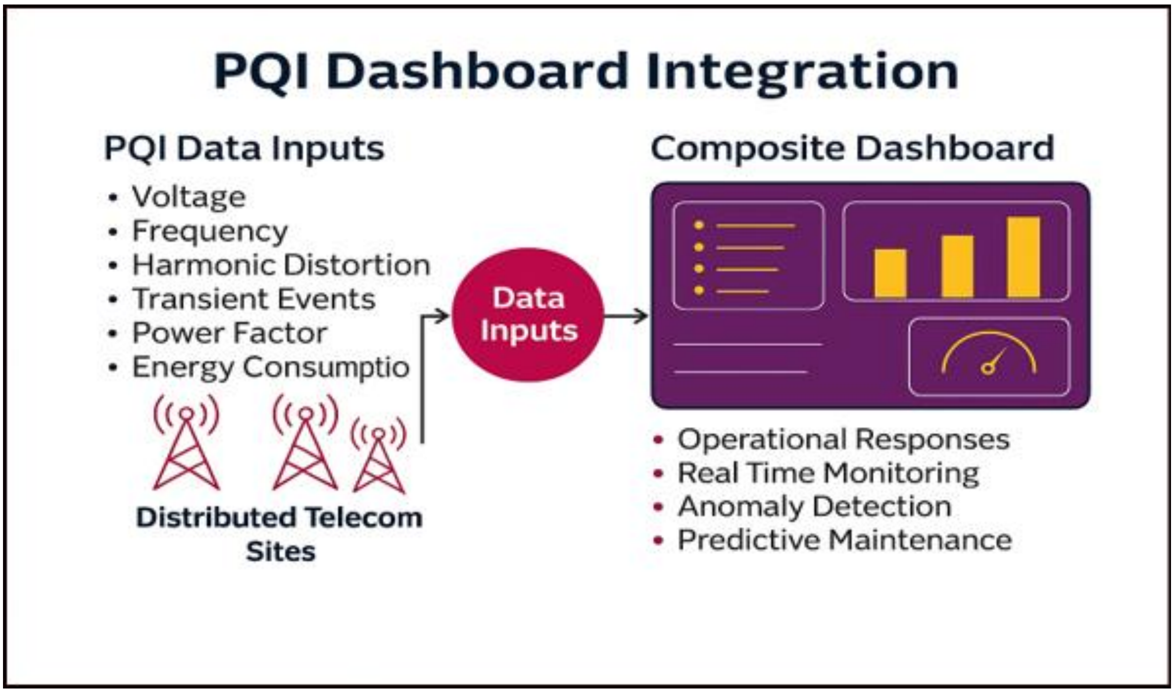

Figure 1: PQI Dashboard Integration – illustrating how PQI data flows from distributed telecom sites into a centralized dashboard and triggers operational responses.

This diagram illustrates how Power Quality Index (PQI) data is collected from distributed telecom sites and integrated into a centralized dashboard for real-time monitoring and operational decision-making.

Key Components:

i. PQI Data Inputs: Voltage stability, frequency consistency, harmonic distortion (THD), power factor, transient events, energy consumption, source switching logs, and load profiles.
ii. Composite Dashboard: Aggregates PQI data, visualizes performance metrics, flags anomalies, and provides actionable insights.
iii. Operational Responses: Enables automated source switching, predictive maintenance, SLA reporting, and energy optimization.

Impact

This integration empowers tower companies to respond proactively to power anomalies, reduce downtime, and improve service reliability for MNOs.

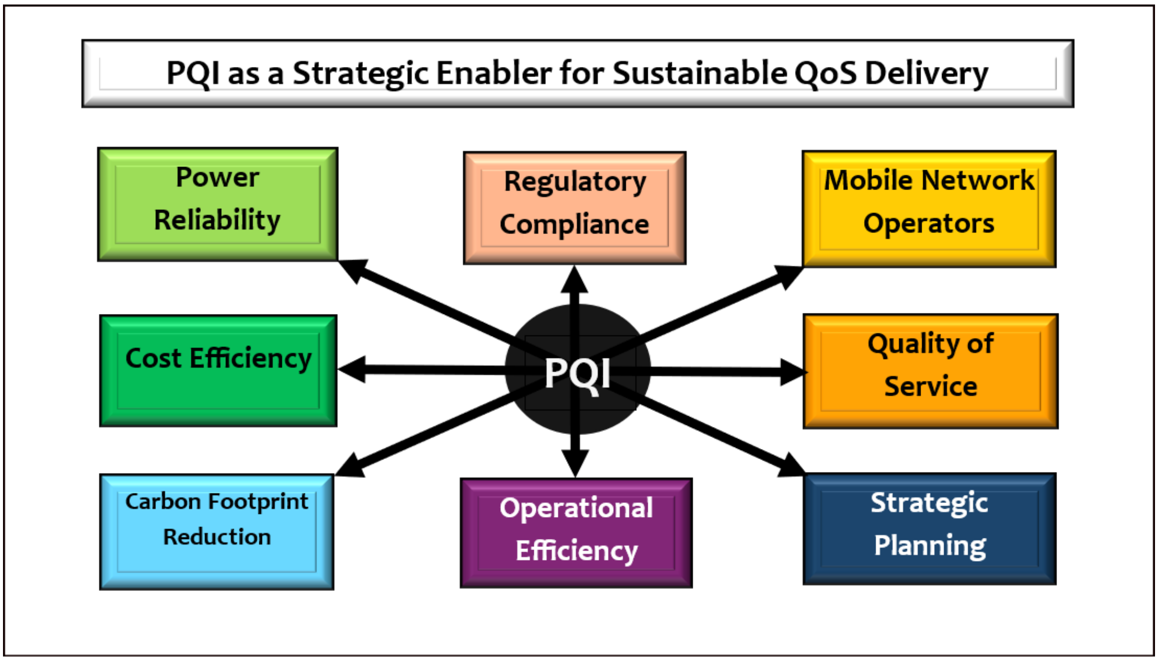

Figure 2: PQI as a Driver of Sustainable QoS Delivery – showing how PQI supports power reliability, cost efficiency, and QoS for MNOs.

This diagram shows how PQI serves as a strategic enabler for sustainable Quality of Service (QoS) delivery by Mobile Network Operators (MNOs).

Key Elements:

i. PQI at the Core: Informs decisions on power reliability, cost efficiency, and infrastructure performance.
ii. Power Reliability: Ensures stable voltage and frequency, reducing equipment failures.
iii. Cost Efficiency: Reduces generator runtime, fuel consumption, and maintenance costs.
iv. QoS Delivery: Supports regulatory compliance and customer satisfaction.

Strategic Benefits:

i. Scalable infrastructure growth
ii. Carbon footprint reduction
iii. Data-driven planning
iv. Stronger MNO–TowerCo partnerships

Research Methodology

This study adopts a field-based, diagnostic methodology to evaluate how tower companies can transition from availability-centric power provisioning to a quality-driven energy management using Power Quality Index (PQI) analytics. The approach is designed to expose inefficiencies in current practices and demonstrate how PQI can enhance power availability, reduce operational costs, and support Mobile Network Operators (MNOs) in delivering consistent Quality of Service (QoS).

Characterization of Existing Tower Company Practices

The research begins by characterizing the operational model of tower companies, which traditionally prioritize power availability over power quality. This model is marked by: Heavy reliance on diesel generators (DGs) with minimal automation, Lack of real-time monitoring and predictive maintenance, Absence of power quality metrics in operational decision-making, Frequent voltage and frequency instability, High fuel consumption and equipment wear.

These practices result in unstable power delivery to MNO equipment, leading to degraded QoS, increased downtime, and poor SLA compliance.

Field Data Collection via RMS Smart Metering

To quantify power quality across telecom tower sites, the study utilizes Root Mean Square (RMS) data collected from smart meters and IoT sensors already deployed at the sites. The following parameters are captured for both AC and DC power sources.

AC Power Parameters: DG capacity (kVA), DG run hours, AC voltage (RMS), AC current (RMS), AC load utilization (%), Frequency (Hz), Generator RPM.

DC Power Parameters: DC plant capacity (Ah), DC voltage (RMS), DC current (RMS), DC load utilization (%).

These measurements are collected over a representative time window to ensure consistency and reliability across different operational conditions.

PQI Computation and Composite Dashboard Integration

This is the core computational engine of the study and focuses on how PQI is calculated with details of the parameters, formulas, and dashboard integration. It includes examples, normalization logic, and composite score construction.

Using the collected RMS data, a Power Quality Index (PQI) is computed for each site's AC and DC power sources. The PQI is derived through a weighted aggregation of key power quality parameters, including Voltage stability, Frequency consistency, Harmonic distortion (if available), Load utilization efficiency, Source switching behavior

The computed PQI values are integrated into a Power Quality Composite Dashboard, which enables: Real-time visualization of power health, Predictive maintenance scheduling, Asset lifecycle tracking, SLA compliance monitoring, Energy source optimization

This section outlines the methodology used to compute the Power Quality Index (PQI) for telecom tower sites and integrate the results into a composite dashboard for operational insights. The PQI is derived from normalized field measurements collected over a period ranging from 14 days, randomly distributed between February and March 2025.

Parameters and Theoretical Basis

Std_Availability (Standard Deviation of Availability)

Definition: Measures the variability in power availability over the measurement period.

Formula:

$$\text{Std\_Availability} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(A_i - \bar{A})} \quad \ldots (2)$$

where A_i is the availability at time *i*, $\bar{A}$ is the mean availability, and *n* is the number of time intervals.

Interpretation: Lower values indicate stable power availability; higher values suggest frequent fluctuations.

In power systems, tolerance bands define the acceptable range around a nominal value—such as 230V for AC voltage or 50Hz for frequency. Deviations beyond these limits can degrade equipment performance and compromise service quality. To evaluate how close each measured parameter is to its ideal condition, we apply normalization using:

$$\textbf{Normalized Score} = 1 - \frac{|\textbf{Measured} - \textbf{Norminal}|}{\textbf{Tolerance Band}} \quad \text{.............................(3)}$$

This ensures:

i. A score of **1** means ideal performance.

ii. A score of **0** means the parameter is at the edge of acceptable limits.

iii. Scores below 0 are clipped, indicating critical degradation.

This approach converts raw electrical measurements into standardized scores that reflect power quality. These scores are then aggregated into an AC/DC Composite Score, which becomes a key input in the enhanced PQI model, helping tower companies monitor electrical health, predict failures, and optimize energy use to support MNOs' QoS delivery.

AC and DC Parameters and Their Normalization:

AC Voltage: Nominal = 230V, Tolerance = ±10V, Formula = (1 - |V - 230| / 10) ....(4)

Frequency: Nominal = 50Hz, Tolerance = ±1Hz, Formula = (1 - |F - 50| / 1) ....(5)

RPM: Nominal = 1500, Tolerance = ±100, Formula = (1 - |RPM - 1500| / 100) ....(6)

AC Load Utilization: Formula = (Load% / 100) ....,,,,,,,,,......................(7)

DC Voltage: Nominal = 48V, Tolerance = ±2V, Formula = (1 - |V - 48| / 2) ....(8)

DC Load Utilization: Formula = (Load% / 100). ....(9)

These six normalized parameters are averaged to form the AC & DC Composite Score.

Formular:

$$\textbf{AC \& DC Composite Score} = \frac{1}{6}\sum_{i=1}^{6} \textbf{Normalized Parameter}_i \quad \text{..(10)}$$

PQI Score

Definition: Composite index representing overall power quality.

Formula:

PQI Score = AC/DC Composite Score ....(11)

Interpretation: Higher scores indicate better power quality and reliability.

Dashboard Integration

The computed PQI scores are visualized through a composite dashboard that enables: Real-time monitoring of power health across sites, Identification of underperforming assets, Predictive maintenance scheduling, Strategic investment planning, SLA compliance tracking

This integrated approach empowers tower companies to optimize energy use, reduce operational costs, and enhance QoS delivery for Mobile Network Operators.

AC/DC Composite Score Calculation:

Example – Site AB0002

This section provides a detailed example of how the AC/DC Composite Score is calculated for Site AB0001. The score is derived from six normalized electrical parameters shown in Table 1, that reflect the site's overall electrical health. Each parameter is normalized between 0 and 1 based on its deviation from nominal values within defined tolerance bands.

Table 1: AB0002 Parameters for AC/DC Composite Score

S/No.	*Parameter*	*Normalized Value*
1	AC Voltage	1.00
2	Frequency	0.81
3	RPM	0.90
4	AC Load Utilization	1.00
5	DC Voltage	0.89
6	DC Load Utilization	1.00

Applying equation (10), we have:

AC/DC Composite Score = (1.00 + 0.81 + 0.90 + 1.00 + 0.89 + 1.00) / 6 = 0.93

And from equation (11), it is clear that the PQI for site AB0002 is 0.93.

A PQI score of 0.93 (on a scale from 0 to 1) signifies that the site's power infrastructure is operating at a high level of efficiency and reliability. The generator and DC rectifier systems are being utilized effectively, while key electrical parameters, such as voltage, frequency, RPM, and load utilization, remain within optimal thresholds. This indicates minimal power disruptions and consistent, high-quality power delivery to mobile network equipment.

Results and Discussion

PQI Score Distribution

The computed Power Quality Index (PQI) scores across telecom tower sites were aggregated using statistical methods, including benchmarking, trend analysis, and predictive modeling, to assess site performance, uncover patterns, and generate actionable insights into power quality behaviour. These analyses help tower companies understand the root causes of power instability, prioritize maintenance, and optimize energy provisioning strategies.

Key Analytical Components

Descriptive Statistics and Std_Availability – Site AB0042

Descriptive statistics such as mean, median, standard deviation, and percentiles are used to summarize PQI scores and their components: generator runtime, grid uptime, battery health, and AC/DC composite scores. These metrics help identify typical performance levels and flag anomalies.

Figure 3 presents the categorical distribution of a sample of 34 telecom tower sites (see Appendix A1, A2 & A3) across Abia, Benue, Ebonyi, and Enugu states, based on their computed Power Quality Index (PQI) scores. Sites were grouped into three performance bands—High, Medium, and Low—to support benchmarking and strategic planning.

The analysis shows that Abia leads with 17 sites in the High PQI category, indicating strong power reliability. Benue and Ebonyi follow with 13 and 10 high-performing sites respectively, while Enugu has a more balanced distribution, including 10 High, 8 Medium, and 4 Low PQI sites. The presence of Low PQI sites, particularly in Enugu and Ebonyi, highlights areas where power instability may require targeted maintenance or energy optimization.

This distribution enables tower companies to prioritize interventions and align infrastructure performance with mobile network operators' (MNOs) quality of service (QoS) objectives.

This chart shows how all the telecom tower sites are grouped into performance bands:

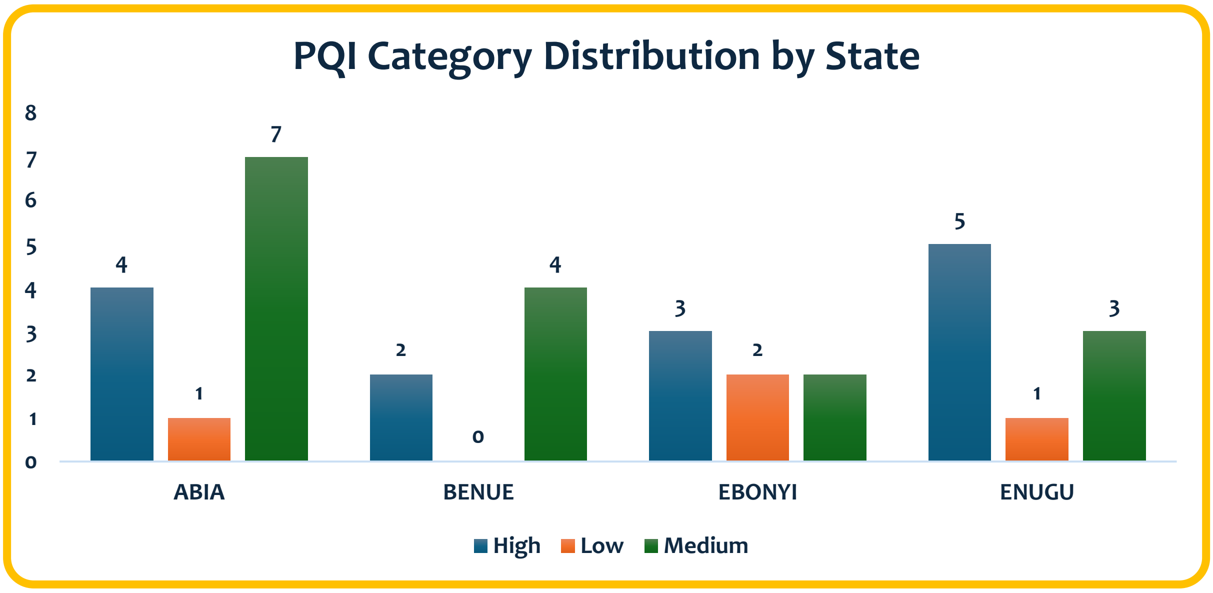

Figure 3: PQI Category Distribution for Sites in the sample State

Sites categorization into three PQI performance levels:

i. High PQI (≥ 0.90): Sites with excellent power quality.

ii. Medium PQI (0.75–0.89): Sites with moderate reliability.

iii. Low PQI (< 0.75): Sites with unstable or poor power quality.

A key component is Std_Availability, which quantifies variability in power availability over time. Even when average availability appears acceptable, high Std_Availability reveals underlying instability. This makes it a critical indicator of power quality degradation, supporting predictive maintenance, energy optimization, and SLA compliance.

The following example in Table 2, from Site AB0042 demonstrates how Std Availability is calculated using 10 sample availability readings.

Table 2: Shows Std_Availability is Calculated using 10 Sample Availability Readings

Time Interval	Availability (%)	Deviation from Mean	Squared Deviation
1	98.86	-0.17	0.0289
2	100.00	0.97	0.9409
3	95.99	-3.05	9.3025
4	98.77	-0.27	0.0729
5	100.00	0.97	0.9409
6	96.73	-2.30	5.2900
7	100.00	0.97	0.9409
8	100.00	0.97	0.9409
9	100.00	0.97	0.9409
10	100.00	0.97	0.9409

Findings

Mean Availability: 99.03%

Standard Deviation of Availability (Std_Availability): 2.183. This value reflects moderate variability in power availability and site data details is presented in Appendix A1.

The correlation between PQI scores and individual parameters such as Std_Availability are examined to understand how fluctuations in power availability impact overall power quality.

For example, a strong negative correlation between Std_Availability and PQI_Score indicates that higher variability in power availability leads to lower power quality.

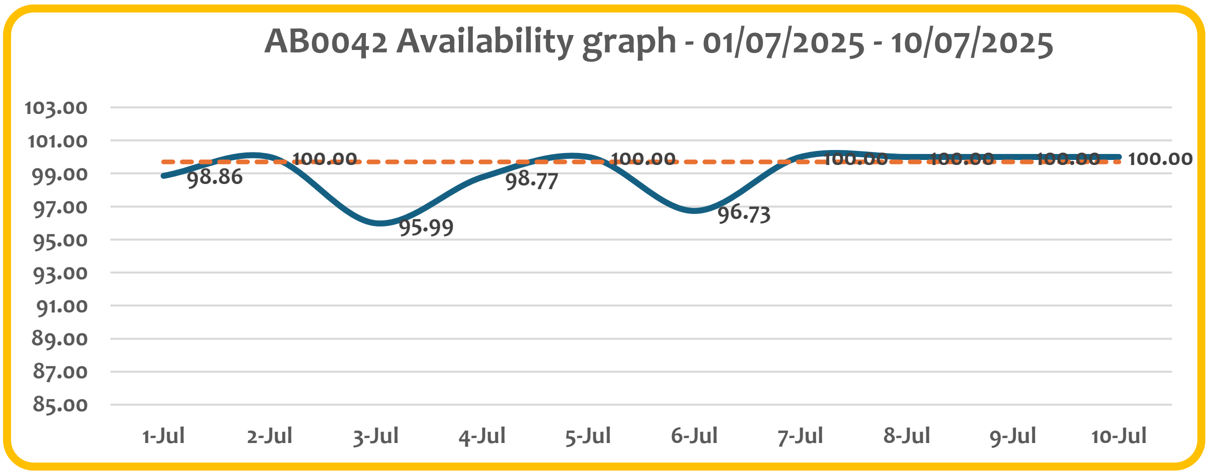

Figure 4: Shows a plot of AB0042 Availability using 10 sample availability readings

Figure 4 shows that availability fluctuated below the 99.70% target line | **34**, with significant dips on July 3 (95.99%) and July 6 (96.73%). This aligns with the statistical analysis, where the mean availability is 99.03% and the standard deviation is 2.183, indicating high variability relative to the 99.70% threshold. These fluctuations highlight the importance of monitoring availability trends, as they directly influence Power Quality Index (PQI) and overall service reliability.

PQI Site Performance Summary

Table 3: PQI Site Performance Summary

State	*PQI Category*	*Site Count*	*Norm AC Volt*	*Norm Freq*	*Norm RPM*	*Norm AC Load Util*	*Norm DC Voltage*	*Norm DC Load Util*	*PQI Score*	*Remarks*
Abia	High	4	0.9961	0.885	0.8705	1	0.9588	1	0.9517	Strong power reliability; minimal intervention needed.
Abia	Medium	7	0.8798	0.9303	0.7555	0.7626	0.8591	0.9619	0.8582	Moderate reliability; consider preventive maintenance.
Abia	Low	1	1	0.824	0.5388	0.3052	0.9328	1	0.7668	Potential power instability; prioritize optimization.
Benue	High	2	0.9571	0.928	0.8998	1	0.9474	1	0.9554	Strong power reliability; minimal intervention needed.
Benue	Medium	4	0.9587	0.875	0.6579	0.9348	0.9307	0.89	0.8745	Moderate reliability; consider preventive maintenance.
Ebonyi	High	3	0.9288	0.916	0.9067	0.8864	0.8335	1	0.9119	Strong power reliability; minimal intervention needed.
Ebonyi	Medium	2	0.9014	0.864	0.6717	0.6448	0.9282	1	0.835	Moderate reliability; consider preventive maintenance.

Ebonyi	Low	2	0.9203	0.912	0.7752	0.206	0.8852	0.9068	0.7676	Potential power instability; prioritize optimization.
Enugu	High	5	0.9765	0.9368	0.7636	1	0.8701	1	0.9245	Strong power reliability; minimal intervention needed.
Enugu	Medium	3	0.91	0.896	0.7513	0.7509	0.8247	1	0.8555	Moderate reliability; consider preventive maintenance.
Enugu	Low	1	0.8553	0.948	0.9091	0.3324	0.9208	0.4988	0.7441	Potential power instability; prioritize optimization.

Overall, this analysis reveals that Enugu and Ebonyi lead with a high number of sites in the High PQI category, reflecting strong power availability and infrastructure reliability. Benue, with no Low PQI sites and a solid average score, also demonstrates consistent performance. In contrast, Abia—despite having several high-performing sites—shows a wider spread across Medium and Low PQI bands. This performance variability positions Abia as a strategic candidate for targeted PQI deployment, enabling TowerCos to address underperforming sites and enhance overall network resilience.

Conclusion

This study has demonstrated that the Power Quality Index (PQI) is a transformative tool for tower companies seeking to shift from availability-centric to quality-driven energy management. By integrating PQI analytics into operational workflows, tower companies can significantly enhance power reliability, reduce operational costs, and support Mobile Network Operators (MNOs) in delivering consistent Quality of Service (QoS).

The research findings confirm that:

i. High PQI scores correlate strongly with stable grid uptime, healthy battery systems, and optimized generator usage.

ii. Sites with low PQI scores exhibit high variability in power availability (Std_Availability), poor battery health, and minimal grid support, all of which compromise service delivery.

iii. Composite dashboards and real-time monitoring enable proactive maintenance, SLA compliance, and strategic planning.

The enhanced PQI model, incorporating AC/DC composite scores, generator runtime, grid uptime, and battery health, provides a robust framework for benchmarking site performance and guiding infrastructure investments.

Recommendations

To fully leverage PQI for operational excellence and QoS assurance, the following recommendations are proposed:

Operational Recommendations for Tower Companies

a. **Adopt PQI Dashboards Across All Sites**
Standardize the use of composite PQI dashboards to enable real-time monitoring, anomaly detection, and predictive maintenance.

b. **Prioritize Low-PQI Sites for Intervention**
Use PQI-based categorization to identify and prioritize underperforming sites for battery replacement, grid restoration, or generator optimization.

c. **Integrate PQI into SLA Metrics**
Align PQI thresholds with SLA targets to ensure that power quality directly supports contractual obligations with MNOs.

d. **Enhance Data Collection Infrastructure**
   Expand the deployment of smart meters and IoT sensors to improve the granularity and accuracy of PQI inputs.

Strategic Recommendations for MNOs and Regulators

a. **Incentivize PQI-Based Energy Management**
   Encourage tower companies to adopt PQI frameworks through regulatory incentives, tax breaks, or performance-based contracts.

b. **Mandate PQI Reporting in Infrastructure Sharing Agreements**
   Require PQI metrics as part of infrastructure sharing SLAs to ensure consistent power quality across shared assets.

c. **Support Capacity Building**
   Invest in training programs for technical staff to interpret PQI data and implement corrective actions effectively.

Future Research Directions

a. **AI-Driven PQI Forecasting**
   Explore the use of machine learning models to predict PQI degradation and automate maintenance scheduling.

b. **PQI in Renewable-Heavy Hybrid Systems**
   Investigate how PQI behaves in systems dominated by solar and battery storage, especially under variable weather conditions.

c. **Cross-Regional Benchmarking**
   Expand the study to include other regions (e.g., PHC, ABJ, LAG, KNO, IBD regions) to

d. develop a national PQI performance map for telecom infrastructure.

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APPENDIX A1: Power Availability (PA) data from 34 sample sites across Abia, Benue Ebonyi & Enugu state - 1st July 2025 to 15th July 2025.

S/No.	SITE ID	State	1-Jul	2-Jul	3-Jul	4-Jul	5-Jul	6-Jul	7-Jul	8-Jul	9-Jul	10-Jul	11-Jul	12-Jul	13-Jul	14-Jul	15-Jul
1	AB0001	ABIA	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
2	AB0002	ABIA	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
3	AB0003	ABIA	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
4	AB0008	ABIA	100.00	100.00	100.00	100.00	99.06	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	98.35
5	AB0019	ABIA	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
6	AB0025	ABIA	100.00	100.00	100.00	100.00	100.00	100.00	100.00	95.98	100.00	100.00	100.00	95.03	100.00	100.00	100.00
7	AB0031	ABIA	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	98.39	100.00	100.00	100.00
8	AB0032	ABIA	100.00	100.00	100.00	100.00	100.00	100.00	98.98	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
9	AB0033	ABIA	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
10	AB0034	ABIA	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
11	AB0036	ABIA	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	96.52	100.00
12	AB0042	ABIA	98.86	100.00	95.99	98.77	100.00	96.73	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
13	BE0002	BENUE	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
14	BE0004	BENUE	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
15	BE0005	BENUE	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
16	BE0009	BENUE	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
17	BE0013	BENUE	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
18	BE0014	BENUE	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
19	EB0002	EBONYI	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
20	EB0004	EBONYI	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.70	100.00	100.00	100.00	100.00
21	EB0007	EBONYI	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.84	100.00	100.00	100.00	96.88	100.00	100.00	100.00
22	EB0008	EBONYI	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	98.61
23	EB0013	EBONYI	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
24	EB0015	EBONYI	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
25	EB0031	EBONYI	98.24	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	96.11	100.00	98.12	97.24	100.00
26	EN0001	ENUGU	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
27	EN0002	ENUGU	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
28	EN0003	ENUGU	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	91.11	100.00	100.00	100.00	100.00	100.00	100.00
29	EN0004	ENUGU	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
30	EN0005	ENUGU	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
31	EN0006	ENUGU	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	98.39
32	EN0007	ENUGU	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
33	EN0010	ENUGU	100.00	100.00	100.00	100.00	100.00	90.32	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
34	EN0011	ENUGU	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

APPENDIX A2: Sites Electrical Parameter and Power Availability data

S/No.	MTN ID	State	Avg_ Avail(%)	Std. Avail	DG Cap (KVA)	AC Volt	AC Current	AC Load Utiliz (%)	Freq (Hz)	RPM	DC Plant Capacity (Ah)	DC Voltage	DC Current	DC Load Utili (%)
1	AB0001	ABIA	99.86	0.79	20	220.11	19.27	80.93	50.15	1469.89	606.85	49.18	24.71	66.33
2	AB0002	ABIA	99.85	0.82	15	234.87	19.92	58.91	50.48	1510.17	705.44	51.45	26.63	70.79
3	AB0003	ABIA	100.00	0.00	20	222.93	15.68	47.99	50.41	1456.07	578.93	53.55	43.28	68.58
4	AB0008	ABIA	99.89	0.36	20	217.46	19.72	77.94	49.94	1491.33	715.95	48.88	22.39	81.67
5	AB0019	ABIA	100.00	0.00	20	228.51	13.54	47.70	49.54	1504.66	647.34	53.83	47.72	59.19
6	AB0025	ABIA	99.71	1.13	20	231.20	8.89	74.71	49.86	1493.60	445.24	53.68	17.19	38.07
7	AB0031	ABIA	99.86	0.55	15	215.01	11.55	81.61	50.33	1524.87	462.53	53.31	36.51	47.36
8	AB0032	ABIA	99.95	0.20	20	215.03	13.90	82.04	50.20	1532.79	574.81	49.29	36.88	69.75
9	AB0033	ABIA	99.78	0.84	20	211.10	6.10	85.21	49.96	1527.12	558.76	51.80	20.09	66.79
10	AB0034	ABIA	99.95	0.28	20	232.09	14.34	92.37	49.56	1453.88	697.42	52.57	22.99	61.86
11	AB0036	ABIA	99.68	1.31	20	229.91	19.72	70.00	49.93	1469.41	632.29	53.92	43.39	70.98
12	AB0042	ABIA	98.00	5.22	20	227.56	19.16	41.54	49.81	1534.25	630.20	49.05	12.47	76.72
13	BE0002	BENUE	99.89	0.64	20	237.92	6.38	43.58	50.01	1503.19	582.81	53.91	24.60	60.76
14	BE0004	BENUE	100.00	0.00	15	213.49	13.99	81.52	49.66	1478.45	642.60	53.27	14.01	38.81
15	BE0005	BENUE	100.00	0.00	20	234.52	14.35	48.40	50.46	1454.71	641.70	53.37	36.95	63.06
16	BE0009	BENUE	100.00	0.00	15	221.42	14.73	64.95	50.35	1516.85	730.86	51.96	10.31	38.68
17	BE0013	BENUE	99.77	1.06	15	236.34	9.01	72.92	50.36	1536.28	570.00	50.07	29.01	66.67
18	BE0014	BENUE	100.00	0.00	20	236.04	5.23	64.16	49.91	1466.29	510.18	53.36	17.71	86.00
19	EB0002	EBONYI	100.00	0.00	20	232.83	12.28	92.76	50.29	1475.71	675.93	52.72	42.84	70.44
20	EB0004	EBONYI	99.97	0.09	20	214.80	10.00	83.52	49.99	1497.95	592.73	53.90	27.40	62.24
21	EB0007	EBONYI	99.81	0.68	20	223.85	16.87	46.76	49.83	1486.73	449.74	48.12	39.09	56.65
22	EB0008	EBONYI	99.92	0.31	20	210.28	11.77	64.47	49.61	1541.38	485.71	52.19	20.78	68.07
23	EB0013	EBONYI	100.00	0.00	20	217.40	7.75	93.18	49.74	1486.83	425.80	49.52	14.01	79.66
24	EB0015	EBONYI	100.00	0.00	20	231.79	17.82	42.83	50.45	1487.34	629.72	48.24	24.10	55.66
25	EB0031	EBONYI	99.45	1.35	15	226.65	18.53	96.52	49.82	1531.79	405.10	53.24	12.96	40.62
26	EN0001	ENUGU	100.00	0.00	15	229.09	18.62	51.39	49.97	1534.04	449.39	53.73	13.04	43.38
27	EN0002	ENUGU	100.00	0.00	20	233.57	12.61	42.34	49.86	1520.13	792.02	48.17	37.82	61.54
28	EN0003	ENUGU	99.63	1.65	15	213.55	7.82	63.51	49.61	1528.90	557.49	49.20	20.11	35.48
29	EN0004	ENUGU	100.00	0.00	20	222.30	6.15	88.14	50.38	1485.10	490.97	49.45	22.46	56.19
30	EN0005	ENUGU	100.00	0.00	20	235.19	15.44	60.47	50.28	1490.47	468.53	50.48	14.84	64.91
31	EN0006	ENUGU	99.95	0.29	20	221.51	10.74	66.65	49.67	1489.37	667.04	49.40	44.59	61.32
32	EN0007	ENUGU	99.97	0.17	15	227.16	17.33	80.54	50.01	1469.19	643.78	50.95	29.74	49.85
33	EN0010	ENUGU	99.48	1.89	20	227.63	14.89	70.53	49.99	1456.12	657.42	53.23	32.89	62.55
34	EN0011	ENUGU	99.68	1.35	20	215.53	16.94	91.69	50.13	1509.09	435.20	52.27	32.78	87.53

APPENDIX A3: Sites normalized data for DG and DC rectifier used for PQI score and composite dashboard calculation for each site

S/No.	MTN ID	State	Avg_ Avail(%)	Std_Avail	Norm_ AC_Volt	Norm_ Freq	Norm_ RPM	Norm_ AC_Load Util	Norm_ DC_ Voltage	Norm_ DC_ Load_ Util	AC_DC Composite Score	PQI Score
1	AB0001	ABIA	99.86	0.79	0.90	0.94	0.70	0.76	0.80	1.00	0.85	0.85
2	AB0002	ABIA	99.85	0.82	1.00	0.81	0.90	1.00	0.89	1.00	0.93	0.93
3	AB0003	ABIA	100.00	0.00	0.93	0.84	0.56	1.00	0.97	1.00	0.88	0.88
4	AB0008	ABIA	99.89	0.36	0.87	0.98	0.91	0.88	0.79	0.73	0.86	0.86
5	AB0019	ABIA	100.00	0.00	0.99	0.82	0.95	1.00	0.98	1.00	0.96	0.96
6	AB0025	ABIA	99.71	1.13	1.00	0.94	0.94	1.00	0.98	1.00	0.98	0.98
7	AB0031	ABIA	99.86	0.55	0.85	0.87	0.75	0.74	0.96	1.00	0.86	0.86
8	AB0032	ABIA	99.95	0.20	0.85	0.92	0.67	0.72	0.80	1.00	0.83	0.83
9	AB0033	ABIA	99.78	0.84	0.81	0.98	0.73	0.59	0.90	1.00	0.84	0.84
10	AB0034	ABIA	99.95	0.28	1.00	0.82	0.54	0.31	0.93	1.00	0.77	0.77
11	AB0036	ABIA	99.68	1.31	1.00	0.97	0.69	1.00	0.99	1.00	0.94	0.94
12	AB0042	ABIA	99.45	1.50	0.98	0.92	0.66	1.00	0.79	0.93	0.88	0.88
13	BE0002	BENUE	99.89	0.64	1.00	1.00	0.97	1.00	0.99	1.00	0.99	0.99
14	BE0004	BENUE	100.00	0.00	0.83	0.86	0.78	0.74	0.96	1.00	0.86	0.86
15	BE0005	BENUE	100.00	0.00	1.00	0.82	0.55	1.00	0.96	1.00	0.89	0.89
16	BE0009	BENUE	100.00	0.00	0.91	0.86	0.83	1.00	0.91	1.00	0.92	0.92
17	BE0013	BENUE	99.77	1.06	1.00	0.86	0.64	1.00	0.83	1.00	0.89	0.89
18	BE0014	BENUE	100.00	0.00	1.00	0.96	0.66	1.00	0.96	0.56	0.86	0.86
19	EB0002	EBONYI	100.00	0.00	1.00	0.88	0.76	0.29	0.94	1.00	0.81	0.81
20	EB0004	EBONYI	99.97	0.09	0.85	1.00	0.98	0.66	0.99	1.00	0.91	0.91
21	EB0007	EBONYI	99.81	0.68	0.94	0.93	0.87	1.00	0.75	1.00	0.92	0.92
22	EB0008	EBONYI	99.92	0.31	0.80	0.84	0.59	1.00	0.92	1.00	0.86	0.86
23	EB0013	EBONYI	100.00	0.00	0.87	0.90	0.87	0.27	0.81	0.81	0.76	0.76
24	EB0015	EBONYI	100.00	0.00	1.00	0.82	0.87	1.00	0.76	1.00	0.91	0.91
25	EB0031	EBONYI	99.45	1.35	0.97	0.93	0.68	0.14	0.96	1.00	0.78	0.78
26	EN0001	ENUGU	100.00	0.00	0.99	0.99	0.66	1.00	0.98	1.00	0.94	0.94
27	EN0002	ENUGU	100.00	0.00	1.00	0.94	0.80	1.00	0.76	1.00	0.92	0.92
28	EN0003	ENUGU	99.63	1.65	0.84	0.84	0.71	1.00	0.80	1.00	0.86	0.86
29	EN0004	ENUGU	100.00	0.00	0.92	0.85	0.85	0.47	0.81	1.00	0.82	0.82
30	EN0005	ENUGU	100.00	0.00	1.00	0.89	0.90	1.00	0.85	1.00	0.94	0.94
31	EN0006	ENUGU	99.95	0.29	0.92	0.87	0.89	1.00	0.81	1.00	0.91	0.91
32	EN0007	ENUGU	99.97	0.17	0.97	1.00	0.69	0.78	0.87	1.00	0.88	0.88
33	EN0010	ENUGU	99.48	1.89	0.98	1.00	0.56	1.00	0.96	1.00	0.92	0.92
34	EN0011	ENUGU	99.68	1.35	0.86	0.95	0.91	0.33	0.92	0.50	0.74	0.74