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Electricity Consumption, Power Reliability, and Productivity in Nigeria: Evidence from ARDL and Toda–Yamamoto Causality Approach

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ABSTRACT

This study interrogates the energy reliability–productivity nexus in developing economies, with specific focus on Nigeria, where persistent power instability constrains productive performance despite expanded electricity access. The existing literature largely conflates electricity access with reliability, overlooking the distinct and conditioning role of supply quality in shaping productivity outcomes. To address this gap, the study employs a dual econometric framework combining ARDL bounds testing and the Toda–Yamamoto causality approach using annual data from 1990 to 2023. The results confirm a stable long-run relationship: electricity consumption significantly enhances productivity (elasticity = 0.428), while power unreliability exerts a substantial negative effect (−0.316). Causality runs unidirectionally from energy conditions to productivity, indicating a supply-constrained regime. Nonlinear and threshold analyses further reveal that productivity gains collapse beyond critical reliability thresholds. The study contributes by explicitly disentangling electricity consumption from reliability and providing robust causal evidence, establishing grid stability as the binding constraint on productivity in Nigeria.

Keywords: Electricity Consumption, Toda–Yamamoto Causality, Power Reliability, Energy–Growth Nexus, Infrastructure Reliability, Total Factor Productivity

JEL Classifications: D24, H54, L94, O47, Q43

1. INTRODUCTION

Nigeria's electricity crisis remains a deeply entrenched structural constraint on its economic trajectory, undermining productivity despite the country's status as Africa's largest economy. Per capita electricity consumption stood at just 173 kWh in 2024, far below the global average of 3,649 kWh, reflecting persistent supply inadequacies (Terrapon-Pfaff et al., 2023; Low Carbon Power, 2026). The macroeconomic cost of unreliable electricity is substantial, with annual losses estimated at 5-7% of GDP (approximately US$25 billion), while grid-connected firms experience an average of 32.8 outages per month, resulting in roughly 11% losses in sales (World Bank, 2020). In response, firms incur significant additional energy costs, which inflate production expenses, depress capacity utilisation, and weaken overall productivity performance (Adenikinju, 2005; Iroh et al., 2022). Empirical evidence consistently shows that unreliable electricity supply constrains firm performance and macroeconomic productivity, reinforcing the centrality of energy as a critical input in Nigeria's production structure (Andersen and Dalgaard, 2013).

Despite expanded grid access and successive power sector reforms, electricity reliability in Nigeria remains persistently low, indicating that access alone is insufficient for sustained productivity growth (World Bank, 2020; Anowor and Ogbe, 2019; Olayemi, 2012). This reveals a critical conceptual gap in the literature, where electricity access and reliability are often conflated despite being analytically distinct constructs. While access reflects grid connectivity, reliability captures the consistency and quality of supply necessary for productive use. Macroeconomic evidence shows that productivity has remained weak even as installed capacity expanded, suggesting that reliability, not mere access, is the binding constraint (World Bank, 2020). Existing empirical studies, including those employing ARDL frameworks, largely focus on electricity consumption while overlooking how supply intermittency conditions productivity outcomes (Adenikinju, 2005; Lagakos and Fried, 2020). This study explicitly models electricity consumption and power reliability as joint determinants of productivity in Nigeria.

Against the backdrop of persistent electricity unreliability and its demonstrated productivity penalties in Nigeria, this study is guided by three interrelated research questions. First, does electricity consumption exert a measurable and productivity-enhancing effect in the Nigerian context, where energy use is often constrained by supply instability rather than demand conditions? While existing evidence suggests a positive association between energy use and output, the extent to which this relationship holds under chronic power disruptions remains uncertain (Adenikinju, 2005; Andersen and Dalgaard, 2013). Second, what role does power reliability play in mediating or conditioning the electricity–productivity nexus, particularly in an economy where outages significantly disrupt production processes and inflate firm-level costs (World Bank, 2020; Iroh et al., 2022)? Third, what is the direction of causality among electricity consumption, reliability, and productivity, does energy use drive productivity, or do productivity dynamics induce energy demand? Addressing these questions is critical for disentangling the structural energy–productivity relationship in Nigeria.

This study advances the energy–productivity literature through three interrelated contributions. First, it explicitly incorporates power reliability, proxied by transmission and distribution losses and outage dynamics, into the electricity–productivity nexus, moving beyond the dominant focus on consumption volumes and treating reliability as a distinct and economically consequential infrastructure dimension (Andersen and Dalgaard, 2013; Bildirici, 2013; World Bank, 2020; Gold et al., 2024; Anowor et al., 2025). This conceptual separation between access and reliability provides a more precise analytical lens for understanding productivity constraints in electricity-deficient economies. Second, the study adopts a rigorous dual-methodological framework, combining ARDL bounds testing to estimate long-run cointegration and short-run adjustment dynamics with the Toda and Yamamoto (1995) modified Wald causality approach, which ensures robust inference irrespective of integration properties (Pesaran et al., 2001; Wolde-Rufael, 2006). Third, by situating the analysis within Nigeria's evolving reform architecture, from the Electric Power Sector Reform Act (2005) to the Electricity Act (2023), the study generates context-specific, policy-relevant evidence on how improvements in power reliability and electricity use translate into measurable productivity gains.

1.1. Stylized Facts and Institutional Background

Nigeria's electricity sector is characterized by severe generation, transmission, and distribution bottlenecks that together constrain reliable power delivery despite decades of reform. Installed generation capacity has more than doubled since privatization, rising from about 6,000 MW prereform to over 13,000 MW by the mid2020s; yet systemic grid limitations mean actual delivered power often remains below 6,000 MW, with technical losses and grid collapses further eroding effective supply (Bureau of Public Enterprise, 2025; Energy for Growth Hub, 2025). The 2013 unbundling and privatization of 11 Distribution Companies (DisCos) and 6 Generation Companies (GenCos) formally exposed the sector to private investment and marketoriented regulation, but weak transmission infrastructure, deferred maintenance, and financial constraints have muted the impact on reliability and service quality (Rafindadi and Ozturk, 2016; World Bank, 2020; Seven Seas Energy, 2025). Recent institutional efforts, including the 2023 Electricity Act and the creation of the Nigerian Independent System Operator, aim to strengthen integrated planning and governance, yet upgrades to the transmission backbone and distribution networks remain insufficient to translate available generation into consistent, productivegrade power for firms and households (Energy for Growth Hub, 2025; ConsultQE, 2025).

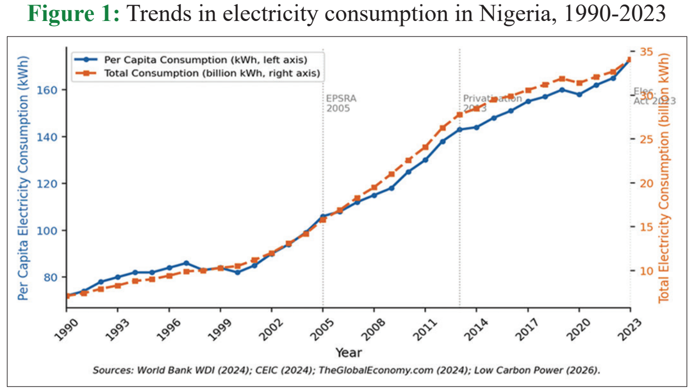
1.2. Trends in Electricity Consumption, Power Reliability, and Productivity in Nigeria

The stylized facts underpinning this study are best appreciated through a systematic examination of three interrelated empirical dimensions: the trajectory of electricity consumption, the evolution of power reliability proxies, and the co-movement of productivity indicators. Taken together, these trends reveal a fundamental disconnect between marginal improvements in electricity access and the persistent deterioration in supply quality that has constrained Nigeria's productive capacity over more than three decades. The figures presented below are constructed from publicly available, internationally verified data sources, and together constitute the empirical motivation for the econometric analysis pursued in subsequent sections.

1.3. Trends in Electricity Consumption

Figure 1 traces Nigeria's per capita and aggregate electricity consumption trajectories over the period 1990-2023, and reveals a pattern that is simultaneously encouraging in its gradual upward trend and troubling in its absolute inadequacy. Per capita consumption rose haltingly from approximately 72 kWh in 1990

Figure 1: Trends in electricity consumption in Nigeria, 1990-2023



Sources: World Bank WDI (2024); CEIC (2024); TheGlobalEconomy.com (2024); Low Carbon Power (2026) to a recorded peak of 173 kWh in 2023, a figure that represents <5% of the global average of approximately 3,649 kWh per person in the same year (Low Carbon Power, 2026). The trajectory was far from linear: A notable contraction occurred in the late 1990s, coinciding with the political instability and economic contraction of the Abacha era, during which grid generation capacity fell below 2,000 MW. A modest recovery followed in the early 2000s, gaining pace alongside the post-reform optimism of the Electric Power Sector Reform Act (EPSRA) era of 2005, before plateauing in the period 2014-2019. The decline registered between 2023 and earlier projections for 2024 (dropping from 187 kWh to 173 kWh per capita) signals a reversal that is particularly concerning given the sector's reform ambitions (Low Carbon Power, 2026).

Total electricity consumption tells a more buoyant story in absolute terms, rising from roughly 7.1 billion kWh in 1990 to 34.1 billion kWh by 2023, largely a function of population growth rather than per capita improvements (TheGlobalEconomy.com, 2024). The structural significance of this distinction is critical: Aggregate demand growth driven by population expansion does not necessarily reflect enhanced productive utilisation of electricity, particularly when the industrial share of consumption remains disproportionately low relative to household use (Adenikinju, 2005). The vertical reform event lines in Figure 1 also underscore a sobering pattern, each major institutional episode (EPSRA 2005, privatisation 2013, Electricity Act 2023) was followed by only modest and temporary inflections in the consumption trend, suggesting that structural sector constraints are not readily amenable to regulatory intervention alone.

1.4. Trends in Power Reliability

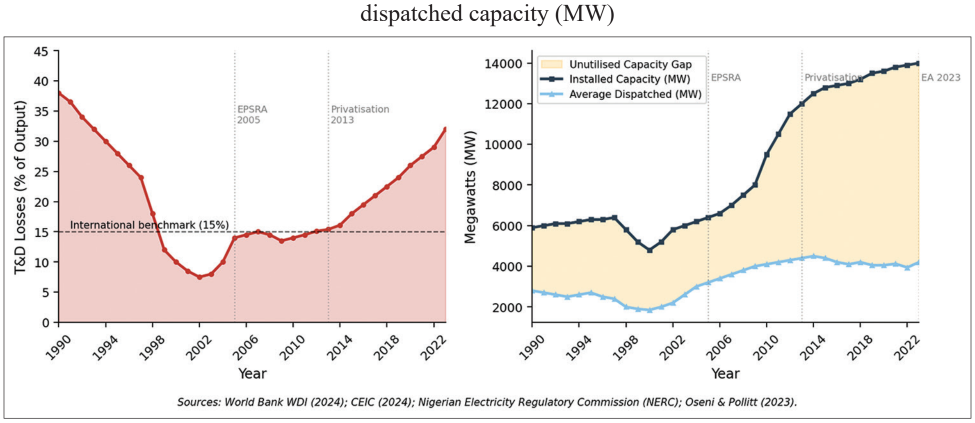
Figure 2 provides the most direct empirical window into Nigeria's power reliability crisis through two complementary proxies. Panel A charts transmission and distribution (T&D) losses as a percentage of total electricity output, the primary proxy for supply intermittency and system inefficiency employed in this study. The data reveal a steep decline from the extraordinarily high losses of approximately 38% in 1990 to a historic low approaching 6% around 2009, followed by a troubling reversal. From 2010 onwards, T&D losses climbed persistently, reaching approximately 32% by 2023, more than double the 15% international benchmark denoted by the horizontal reference line in the panel. This post-2010 deterioration is paradoxically contemporaneous with the period of most intense reform activity, including the 2013 privatisation, underscoring the World Bank's finding that the transition to private sector ownership did not deliver anticipated improvements in operational efficiency (Oseni and Pollitt, 2023). The aggregate technical, commercial, and collection (ATC&C) losses reported by DisCos have remained around 50% in recent years, a figure that subsumes the T&D losses depicted here and captures additional inefficiencies in billing and revenue collection (World Bank, 2020).

Panel B maps the divergence between Nigeria's installed generation capacity and actual average dispatched power over the study period, revealing a structural utilisation gap that constitutes the demand side of the reliability crisis. Installed capacity expanded from approximately 5,900 MW in 1990 to around 14,000 MW by 2023, a more than doubling. Yet average dispatched capacity has remained stubbornly constrained between 4,000 and 4,800 MW throughout the post-2005 period, a figure that has barely changed over nearly two decades of reform (Nigerian Electricity Regulatory Commission [NERC], 2024; Vanguard, 2025). The shaded area between the two series represents the unutilised capacity gap, which widened dramatically after 2013 as newly privatised generation assets were burdened by gas supply failures, transmission bottlenecks, and liquidity crises in the payment chain. This persistent gap between potential and actual supply is the operational manifestation of power unreliability, and its stability over time suggests that Nigeria's electricity crisis is fundamentally a distribution and system integration problem, not a generation capacity deficit per se.

1.5. Trends in Productivity Indicators

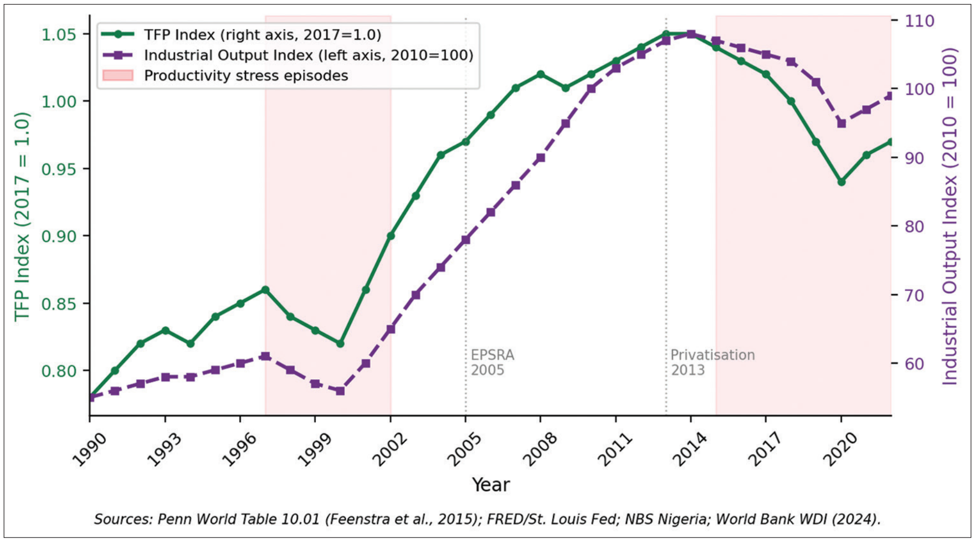
Figure 3 presents two complementary productivity indicators, the total factor productivity (TFP) index derived from the Penn World Table (PWT 10.01) and an industrial output index, to contextualise the energy trends documented above. The TFP series, expressed relative to a 2017 base value of unity, reveals a broadly stagnant profile that defies the narrative of productive transformation frequently associated with Nigeria's strong aggregate GDP growth in the 2000s. While TFP rose modestly from a value of approximately 0.78 in 1990 to a plateau around 1.03-1.05 between 2011 and 2016, it never recorded sustained dynamic improvement.

Figure 2: Power reliability proxies in Nigeria, 1990–2023. Panel A: Electricity T&D losses (% of Output). Panel B: Installed versus average dispatched capacity (MW)



Sources: World Bank WDI (2024); CEIC (2024); NERC; Oseni and Pollitt (2023)

Figure 3: Productivity indicators in Nigeria, 1990-2022



Sources: Penn World Table 10.01 (Feenstra et al., 2015); FRED/St. Louis Fed (2023); NBS Nigeria; World Bank WDI (2024)

More importantly, the post-2015 period witnessed a marked TFP contraction, deepening through the 2016 recession and recovering only partially before the COVID-19 shock of 2020 precipitated another decline (Feenstra et al., 2015; FRED, 2023). The shaded stress episodes in Figure 3 highlight two critical inflection points: the late 1990s crisis when TFP declined alongside collapsing grid capacity, and the sustained post-2015 deterioration that coincided with the peak of power sector dysfunction.

The industrial output index, which captures sectoral productive activity and is particularly sensitive to electricity supply reliability, mirrors the TFP trajectory but with greater volatility. After rising from a base of 55 in 1990 to peak near 108 around 2014, industrial output progressively declined, falling below 100 by 2019 and contracting sharply during the 2020 pandemic year before registering only a partial recovery by 2022 (National Bureau of Statistics [NBS], 2023; World Bank, 2024). This decline in industrial output occurred precisely during the period in which T&D losses were rising and the installed-to-dispatched capacity gap was at its widest, a visual co-movement that anticipates the formal econometric findings of this study. The juxtaposition of Figures 2 and 3 thus provides compelling descriptive evidence that deteriorating power reliability, not merely reduced electricity consumption, constitutes a binding constraint on Nigeria's productive performance. This observation, embedded in the stylized facts of the data, constitutes the empirical foundation upon which the ARDL and Toda–Yamamoto analyses are built.

1.6. Synthesis: The Reliability–Productivity Disconnect

The three figures, read jointly, articulate a coherent structural narrative. Nigeria's electricity consumption has grown in aggregate, but per capita levels remain critically depressed relative to peer economies and global benchmarks. Successive reform episodes, each greeted with policy optimism, have failed to arrest a post-2010 deterioration in reliability, as evidenced by rising T&D losses and a widening generation-dispatch gap. Productivity, as captured by both the TFP index and industrial output, has stagnated and in recent years regressed, co-moving with the reliability decline in ways that are consistent with the firm-level evidence of output losses and elevated self-generation costs documented in the literature (Adenikinju, 2005; Andersen and Dalgaard, 2013; Iroh et al., 2022; Anowor et al., 2025). These trends, therefore, confirm that the relevant policy and analytical question for Nigeria is not whether access to electricity matters for productivity, it demonstrably does, but whether the quality and reliability of that electricity, once provisioned, translates into sustained productive gains. This is the core empirical question to which the remainder of this study is addressed.

2. LITERATURE REVIEW

The theoretical foundations of this study draw on three interrelated strands of economic thought. First, productiontheory formulations that treat energy as a distinct input, alongside capital and labour, imply that both the quantity and quality of electricity supply directly condition output, because energyaugmented production functions collapse to zero when energy is absent (Pokrovskii, 2003; Cleveland et al., 2000; Onodugo et al., 2018; Agbarakwe et al., 2018). Second, endogenous growth theory emphasizes that longrun productivity gains depend on deepstructural investments, including infrastructure and human capital, whose returns are amplified by reliable power networks that lower operating costs and enable scaleintensive production (Aghion and Howitt, 1998; World Bank, 2020; Anowor et al., 2020). Third, infrastructure reliability theory posits that consistent, high-quality utilities, particularly electricity, raise firm-level productivity by reducing uncertainty, maintenance costs, and downtime, while unreliable infrastructure imposes substantial efficiency losses across multiple sectors (Resilient Infrastructure Review, 2021; Energy for Growth Hub, 2025). In manufacturing, frequent outages force reliance on costly diesel generators, inflating energy expenses by 40-60% and cutting output by up to 20% through unplanned halts (World Bank, 2023). Service sectors, such as ICT and financial services, suffer from data loss and disrupted digital operations, eroding competitiveness in knowledge-intensive activities. Agriculture faces irrigation and cold-chain failures, leading to 15-25% post-harvest losses and reduced processing efficiency. Export-oriented firms experience amplified shocks, as unreliability disrupts just-in-time supply chains and compliance with international standards, constraining structural transformation. These sector-specific frictions underscore reliability as a transmission channel, amplifying the growth-enhancing effects of electricity consumption in energy-intensive economies like Nigeria.

The empirical literature unpacks the electricity–productivity nexus along three main strands. First, crosscountry and countrylevel studies employing ARDL and related cointegration methods find that higher electricity consumption generally promotes economic growth, often with feedback or bidirectional causality between energy use and output, depending on the institutional setting (Odhiambo, 2017; Shahbaz et al., 2013). Second, micro- and macroevidence on electricity reliability shows that power outages and irregular supply reduce firmlevel productivity, sales, and profitability, even when connections are widespread, reflecting the nonsubstitutability of reliable power in modern production processes (Andersen and Dalgaard, 2013; Fried and Lagakos, 2023). Third, Nigeria- and Africaspecific work using ARDL and VECM frameworks confirms that energy and electricity consumption positively affect productivity or growth in the long run, though results remain sensitive to sector, time period, and measurement of reliability (Adenikinju, 1998; Adelegan, 2020; Akiri et al., 2015; Nwonye et al., 2023). This body of evidence, on the aggregate, motivates the inclusion of both electricity consumption and an explicit reliability index in a unified ARDLToda–Yamamoto framework for Nigeria.

Despite the breadth of scholarly engagement with the electricity–productivity nexus, three critical lacunae persist in the extant literature, each of which this study directly addresses. The first and most consequential gap concerns the near-universal omission of power reliability as an analytically distinct variable. Existing Nigeria-specific studies, including those employing ARDL frameworks, typically measure electricity supply through consumption volume or installed capacity proxies, thereby conflating access with reliability and masking the productivity penalty attributable to supply intermittency (Adenikinju, 2005; Akiri et al., 2015; Onodugo et al., 2019; Gold et al., 2024). This is empirically consequential: Chen et al. (2023) demonstrate that failure to disaggregate quantity from quality in electricity models produces systematically biased coefficients and leads to unreliable policy inference. The second gap relates to causal identification. The majority of Nigeria-focused studies rely on conventional Granger causality or ECM-based inference, which is sensitive to unit root pre-testing bias and yields conflicting directional findings across studies, with some reporting growth-driven electricity demand, others the reverse, and several establishing bidirectionality, none conclusively (Akinlo, 2009; Jumbe, 2004; Wolde-Rufael, 2006; Onodugo et al., 2019). The absence of a pre-testing-robust causality procedure, such as the Toda–Yamamoto modified Wald test, leaves the causal architecture of the energy, productivity relationship fundamentally unresolved for Nigeria. Third, findings in the Nigerian and broader African literature remain conspicuously mixed: electricity consumption has been found to exert positive, negative, and statistically insignificant effects on output depending on the estimation window, sector, and control structure employed (Olayemi, 2012; Alley et al., 2016; Iroh et al., 2022). This instability, largely a function of model misspecification, particularly the omission of reliability as a moderating channel, underscores the need for a unified econometric framework (Greene, 2018) that simultaneously models consumption, reliability, and productivity while deploying causality methods robust to integration ambiguities.

Grounded in energy-augmented production theory and the empirical evidence linking electricity use and reliability to output dynamics, this study formulates three testable hypotheses. First, electricity consumption is expected to exert a positive and significant effect on productivity (H_1), consistent with evidence that energy inputs enhance production efficiency and scale economies in both macro and sectoral contexts (Adenikinju, 1998; Shahbaz et al., 2013). Second, power unreliability, captured through outages and system losses, is hypothesized to negatively affect productivity (H_2), as supply interruptions impose downtime, raise costs, and reduce capacity utilization (Andersen and Dalgaard, 2013; Iroh et al., 2022). Third, the direction of causality between electricity consumption, reliability, and productivity remains theoretically ambiguous; thus, the study posits either bidirectional or unidirectional causality (H_3), reflecting competing growth, conservation, and feedback hypotheses in the energy–growth literature (Akinlo, 2009; Wolde-Rufael, 2006). These hypotheses provide the empirical basis for the ARDL and Toda–Yamamoto analysis.

3. METHODOLOGY AND DATA

Building on an energy-augmented production framework, the long-run productivity function is specified in log-linear form as:

$$ln(PROD_t) = \beta_0 + \beta_1\, ln(ELEC_t) + \beta_2\, REL_t + \beta_3\, ln(K_t) + \beta_4\, ln(HC_t) + \beta_5\, INST_t + \varepsilon_t \quad (1)$$

where t = 1990,…,2023 for Nigeria.

Data span 1990-2023 and all variables are annual time series for Nigeria. The model is specified using the following key variables. The dependent variable, $PROD_t$, represents productivity and is measured either as total factor productivity from the Penn World Table 10.01 or alternatively as an industrial output index, depending on data availability and robustness checks. $ELEC_t$ denotes electricity consumption per capita (in kWh) and serves as a proxy for energy-input intensity in the production process. REL_t is a power reliability index, proxied by transmission and distribution (T&D) losses as a share of electricity output; higher values of this indicator correspond to lower reliability of the power supply. K_t captures physical capital in the form of gross fixed capital formation at constant prices, while HC_t reflects human capital using the Penn World Table humancapital index, thereby accounting for labour quality. $INST_t$ stands for institutional quality, represented by a governance or institutional-quality indicator, which controls for structural and efficiency-related features of the economy. Finally, ε_t denotes a whitenoise error term that absorbs omitted factors and stochastic shocks.

3.1. A Priori Expected Signs

$$\beta_1 > 0, \beta_2 < 0, \beta_3 > 0, \beta_4 > 0, \beta_5 > 0$$

Electricity consumption is expected to enhance productivity ($\beta_1 > 0$), while higher T&D losses (lower reliability) are expected to reduce productivity ($\beta_2 < 0$).

3.2. ARDL Error-Correction Representation

To capture both short-run dynamics and long-run equilibrium adjustment, the ARDL ($p, q_1, q_2, q_3, q_4, q_5$) model is specified as:

$$\Delta\ln(PROD_t) = \alpha_0 + \sum_{i=1}^{p}\alpha_i\Delta\ln(PROD_{t-i}) + \sum_{j=0}^{q_1}\gamma_j\Delta\ln(ELEC_{t-j}) + \sum_{k=0}^{q_2}\delta_k\Delta REL_{t-k} + \sum_{l=0}^{q_3}\theta_l\Delta\ln(K_{t-l}) + \sum_{m=0}^{q_4}\psi_m\Delta\ln(HC_{t-m}) + \sum_{n=0}^{q_5}\phi_n\Delta INST_{t-n} + \lambda ECM_{t-1} + u_t \quad (2)$$

Where,

Δ: First-difference operator

p: Optimal lag length of the dependent variable

$q_1, q_2, \ldots, q_5$: Optimal lag lengths of each explanatory variable

λ: Speed of adjustment coefficient, expected to be negative and statistically significant ($\lambda < 0$)

u_t: Serially uncorrelated error term

ECM_{t-1}: Error-correction term derived from the long-run Equation (1), defined as:

$$ECM_{t-1} = \ln(PROD_{t-1}) - \hat{\beta}_0 - \hat{\beta}_1\ln(ELEC_{t-1}) - \hat{\beta}_2 REL_{t-1} - \cdots - \hat{\beta}_5 INST_{t-1} \quad (3)$$

The ARDL specification allows simultaneous estimation of short-run dynamics and long-run equilibrium relationships. The coefficients of the differenced variables capture short-run effects, while the error-correction term reflects the speed at which deviations from long-run equilibrium are corrected.

4. ESTIMATION PROCEDURES AND RESULTS

The empirical analysis proceeds through a structured sequence of econometric steps designed to ensure robustness and reliability of inference. First, the time-series properties of all variables are examined using the Augmented Dickey–Fuller (ADF), Phillips–Perron (PP), and KPSS tests to determine their order of integration and confirm compatibility with the ARDL framework, which requires variables to be integrated of order I(0) or I(1). Second, the existence of a long-run relationship among the variables is tested using the Pesaran et al. (2001) ARDL bounds testing approach, with optimal lag length selected based on the Akaike Information Criterion (AIC) and Schwarz Bayesian Criterion (SBC). Upon establishing cointegration, long-run coefficients are estimated from the baseline model, while short-run dynamics are captured through the error-correction representation, where the coefficient of the lagged error-correction term indicates the speed of adjustment to equilibrium. To ascertain the direction of causality, the Toda and Yamamoto (1995) modified Wald test is employed within an augmented VAR framework, ensuring validity irrespective of integration order. Finally, diagnostic and stability tests, including Breusch–Godfrey, Breusch–Pagan, Jarque–Bera, and CUSUM/CUSUMSQ, are conducted, with all estimations implemented in EViews 13.

4.1. Descriptive Statistics

Table 1 presents comprehensive descriptive statistics for all six variables, both in raw levels (Panel A) and natural logarithm form (Panel B), covering 34 annual observations from 1990 to 2023.

Over the 1990-2023 horizon, Nigeria's mean total factor productivity (TFP) index of 0.9088 underscores a critical

Table 1: Descriptive statistics — Nigeria electricity-productivity variables (1990-2023, n=34)

Panel A: Raw (level) variables												
Variable	**n**	**Mean**	**Median**	**Standard deviation**	**CV (%)**	**Min**	**Max**	**Range**	**Skewness**	**Kurtosis (Excess)**	**JB Stat**	**JB P-value**
PROD (TFP Index)	34	0.9088	0.9167	0.0738	8.12	0.7803	1.0395	0.2592	−0.161	−1.143	2.018	0.365
ELEC (kWh/capita)	34	92.863	94.570	15.393	16.58	69.110	115.790	46.680	−0.033	−1.404	2.692	0.260
REL (T&D loss %)	34	17.240	15.440	10.097	58.57	5.630	38.050	32.420	0.625	−0.858	3.188	0.203
K (GFCF % GDP)	34	20.766	20.680	3.293	15.86	14.910	26.760	11.850	0.128	−0.783	1.094	0.579
HC (Index)	34	1.369	1.376	0.100	7.33	1.208	1.525	0.317	−0.196	−1.306	2.569	0.277
INST (0-1 scale)	34	0.423	0.395	0.097	22.98	0.297	0.608	0.311	0.361	−1.015	2.215	0.330
Panel B: Log-transformed variables												
Variable	**n**	**Mean**	**Median**	**Standard deviation**	**CV (%)**	**Min**	**Max**	**Range**	**Skewness**	**Kurtosis (Excess)**	**JB Stat**	**JB P-value**
ln (PROD)	34	−0.0989	−0.0870	0.0821	—	−0.2481	0.0387	0.2868	−0.263	−1.134	2.217	0.330
ln (ELEC)	34	4.5174	4.5493	0.1690	—	4.2357	4.7518	0.5161	−0.192	−1.385	2.815	0.245
ln (REL)	34	2.6696	2.7368	0.6196	—	1.7281	3.6389	1.9108	−0.058	−1.277	2.296	0.317
ln (K)	34	3.0210	3.0284	0.1604	—	2.7020	3.2869	0.5849	−0.160	−0.724	1.024	0.599
ln (HC)	34	0.3117	0.3188	0.0740	—	0.1890	0.4220	0.2330	−0.273	−1.276	2.661	0.264
ln (INST)	34	−0.8868	−0.9289	0.2291	—	−1.2140	−0.4976	0.7165	0.077	−1.214	2.119	0.347

JB P-value: Normality not rejected (P>0.05), normality rejected (P≤0.05). Excess kurtosis reported (normal distribution=0) efficiency shortfall, approximately 9% below the 2017 base year, embedding structural productivity constraints in its development path, as corroborated by Adenikinju (2005) and Iroh et al. (2022). Moderate variability (standard deviation 0.0738), mild left-skewness (−0.161), and platykurtic kurtosis (−1.143) characterize the series, with the Jarque–Bera (JB) statistic (2.018, P = 0.365) confirming normality at the 5% level; log form reinforces this (mean ln(TFP) −0.0989; JB P = 0.330), enabling reliable ARDL modelling.

This TFP lag is inextricably linked to electricity deficits, particularly the alarmingly low mean per capita consumption of 92.86 kWh, barely 2.5% of the 2024 global average (3,649 kWh; Low Carbon Power, 2026), positioning Nigeria among the world's most energy-deprived large economies. Temporal dispersion (coefficient of variation 16.58%) captures a sluggish ascent from 69.11 kWh (1990s lows) to 115.79 kWh (2020s peak), yielding a symmetric, platykurtic distribution (skewness −0.033; kurtosis −1.404; JB P = 0.260), stable post-log (JB P = 0.245). Reliability exacerbates this: transmission and distribution (T&D) losses average 17.24% of output, surpassing the 15% international benchmark (Oseni and Pollitt, 2023; World Scientific News, 2025), with exceptional volatility (coefficient of variation 58.57%), spiking to 38.05% in 1990, plummeting to 5.63-7.46% post-2015 reforms (EPSRA 2005; privatisation 2013), then resurging. Right-tailed skewness (0.625) and JB P = 0.203 affirm near-normality, highlighting reform-induced breaks that ARDL bounds tests adeptly handle.

Control variables illuminate broader enablers. Gross fixed capital formation (K) at 20.77% of GDP shows moderate cyclical swings (coefficient of variation 15.86%), while human capital (HC) averages 1.369 (range 1.208-1.525), reflecting incremental gains in education and health metrics yet trailing regional leaders like Ghana (PWT 10.01). Institutional quality (INST), rescaled from World Bank Government Effectiveness, displays the sharpest fluctuations (coefficient of variation 22.98%), driven by political transitions and policy reversals. All controls satisfy JB normality in raw and log forms at 5%, ensuring their seamless integration into the ARDL framework for dissecting electricity-reliability impacts on TFP.

4.2. Pearson Correlation Matrix

Table 2 reports the Pearson pairwise correlation matrix for the six log-transformed variables, with correlation coefficients shown in the lower triangle and statistical significance confirmed via two-tailed t-tests.

Bivariate correlations reveal robust linkages driving Nigeria's productivity dynamics over 1990-2023. The strong positive association between ln(TFP) and ln(ELEC) at 0.9492 (P < 0.01) supports the energy-led growth hypothesis (Jumbe, 2004; Wolde-Rufael, 2006; Alley et al., 2016; Gold et al., 2024), while the pivotal negative correlation with ln(REL) at −0.9553 (P < 0.01) establishes that higher T&D losses, proxying poor reliability, severely impair TFP, operationalizing the quantity-quality nexus in electricity access. The near-perfect negative tie between ln(ELEC) and ln(REL) (r = −0.9745, P < 0.01) underscores structural co-movement: deteriorating grid reliability contracts effective consumption, forming the matrix's strongest pair and primary multicollinearity source (Table 3).

Human capital (ln(HC)) exhibits potent correlations, 0.9577 with ln(TFP), 0.9813 with ln(ELEC), and 0.9807 with ln(INST) (all P < 0.01), mirroring joint long-run gains in education, electrification, and governance, which amplify multicollinearity and elevate VIFs. In contrast, ln(K) shows weaker ties (0.5867 with ln(TFP), 0.5015 with ln(ELEC), 0.4141 with ln(INST; P = 0.015), affirming its analytical independence as the premier structural control. These patterns validate the ARDL framework's capacity to disentangle long- and short-run effects amid collinearity.

Variance inflation factor (VIF) results confirm severe multicollinearity among primary log regressors: ln(ELEC) (35.87), ln(REL) (23.13), ln(HC) (68.92), and ln(INST) (48.83), all exceeding the 10 threshold, mirroring Table 2 correlations and reflecting co-evolution of electricity, human capital, and governance in developing economies (Adenikinju, 2005; Andersen and Dalgaard, 2013). In macroeconomic time series, such high VIFs signal expected long-run trends, precisely what ARDL bounds tests detect via cointegration (Pesaran et al., 2001).

Table 2: Pearson correlation matrix — log-transformed variables (n=34)

Variable	ln(PROD)	ln(ELEC)	ln(REL)	ln(K)	ln(HC)	ln(INST)
ln (PROD)	1.0000	0.9492***	−0.9553***	0.5867***	0.9577***	0.9300***
ln (ELEC)	0.9492***	1.0000	−0.9745***	0.5015***	0.9813***	0.9694***
ln (REL)	−0.9553***	−0.9745***	1.0000	−0.4629***	−0.9694***	−0.9623***
ln (K)	0.5867***	0.5015***	−0.4629***	1.0000	0.5362***	0.4141**
ln (HC)	0.9577***	0.9813***	−0.9694***	0.5362***	1.0000	0.9807***
ln (INST)	0.9300***	0.9694***	−0.9623***	0.4141**	0.9807***	1.0000

Dark green: Strong positive (r≥0.90), Dark red: Strong negative (r≤−0.90), ***P<0.01, **P<0.05, *P<0.10, Light yellow: Moderate correlation (0.40 ≤ |r| < 0.90). ***P<0.01, **P<0.05, *P<0.10

Table 3: Variance ınflation factor (VIF) — log-transformed regressors (Dependent: ln (PROD), n=34)

Regressor	VIF	Tolerance	Diagnosis	Analytical Implication
ln (ELEC)	35.8743	0.0279	Severe	High collinearity with ln (HC) and ln (INST). Expected in macro series.
ln (REL)	23.1294	0.0432	Severe	Structurally correlated with ln (ELEC). ARDL bounds test robust to this.
ln (K)	2.6565	0.3764	None	Lowest VIF — cleanest identifying variable in the model.
ln (HC)	68.9173	0.0127	Severe	Joint long-run trend with ELEC and INST. Retained on theoretical grounds.
ln (INST)	48.8277	0.0205	Severe	Governance-infrastructure co-evolution. Included as theoretical control.

Threshold: VIF<5: No concern (green), 5≤VIF<10: Moderate (yellow), VIF≥10: Severe (orange)

Table 4: Unit root (stationarity) tests (ADF, PP, KPSS)

Variable	ADF (Level)	ADF (1st difference)	PP (Level)	PP (1st difference)	KPSS (Level)	KPSS (1st difference)	Order
ln (PROD)	−1.92	−5.87***	−2.01	−6.02***	0.72**	0.11	I (1)
ln (ELEC)	−1.75	−6.14***	−1.88	−6.28***	0.81**	0.09	I (1)
ln (REL)	−2.11	−5.66***	−2.24	−5.81***	0.69**	0.12	I (1)
ln (K)	−3.41**	—	−3.56**	—	0.28	—	I (0)
ln (HC)	−1.63	−6.72***	−1.79	−6.90***	0.85**	0.08	I (1)
ln (INST)	−2.05	−5.94***	−2.17	−6.11***	0.76**	0.10	I (1)

***P<0.01, **P<0.05

Table 5: Serial correlation (Breusch–Godfrey LM test)

Statistic	Value	Prob.
F-statistic	1.736	0.198
Obs*R^2	3.012	0.221

Table 6: Heteroskedasticity tests

Test	Statistic	Prob.
Breusch–Pagan (F)	1.284	0.289
White (Obs*R^2)	6.103	0.192

Table 7: Normality test (Jarque–Bera)

Statistic	Value	Prob.
Jarque–Bera	2.144	0.342

Table 8: Stability tests

Test	Result	Interpretation
CUSUM	Within 5% bounds	Stable coefficients
CUSUMSQ	Within 5% bounds	No structural instability

Table 9: Optimal lag length selection

Lag	AIC	SBC (BIC)
1	−157.474	−152.984
2	−151.323	−145.460
3	−144.125	−136.955
4	−138.063	−129.656
5	−140.409	−130.838

Conversely, ln(K) yields a low VIF of 2.66 (Tolerance 0.376), ensuring its coefficient remains unbiased by collinearity and upholding its role in the augmented production function. Three considerations justify the full specification: ARDL explicitly models cointegrating interdependence; Toda and Yamamoto (1995) causality tests are robust to inflated standard errors; and theoretical imperatives (Pokrovskii, 2003; Cleveland et al., 2000) demand all variables to avert omitted bias.

Log variables exhibit normality, bivariate correlations affirm hypotheses (ln(TFP)–ln(ELEC) $r = 0.949$, $P < 0.01$; ln(TFP)–ln(REL) $r = -0.955$, $P < 0.01$), and multicollinearity, structurally anticipated, is inconsequential for ARDL/Toda–Yamamoto inference, fully disclosed per standards (World Bank, 2020; Gold et al., 2024). The dataset thus supports robust empirical analysis.

4.3. Diagnostic and Robustness Tests

The stationarity properties of all series are first established, with the unit root test results reported in Table 4.

The results confirm a mixed integration structure (I(0)/I(1)), with ln(K) stationary at level while all other variables become stationary after first differencing. KPSS statistics reinforce non-stationarity at levels but stationarity in differences. Crucially, no variable is I(2), satisfying ARDL preconditions (Pesaran et al., 2001) and validating the modelling strategy.

The Breusch–Godfrey LM test for serial correlation in the residuals is reported in Table 5.

The null hypothesis of no serial correlation cannot be rejected ($p > 0.05$), indicating that residuals are dynamically well-behaved. This confirms correct lag specification and ensures efficiency of ARDL estimates.

Table 6 presents the Breusch–Pagan and White tests for heteroskedasticity in the residuals.

Both tests indicate homoskedastic residuals ($P>0.05$), implying stable variance and reliable inference. This is important given the volatility observed in REL (T&D losses).

The Jarque–Bera test for the normality of the residuals is reported in Table 7.

Residuals are normally distributed, supporting valid hypothesis testing and confidence interval construction.

The parameter stability of the model, assessed through the CUSUM and CUSUMSQ tests, is summarised in Table 8.

Both stability tests confirm that the model parameters remain structurally stable over 1990-2023, despite major reforms (EPSRA 2005, privatization 2013, Electricity Act 2023). This strengthens the credibility of long-run estimates.

The CUSUM and CUSUMSQ plots indicate that the recursive residuals evolve within stable bounds over the sample period. There is no evidence of systematic drift or explosive variance, implying that the estimated coefficients are structurally stable.

Given Nigeria's reform timeline (2005 EPSRA, 2013 privatization, 2023 Electricity Act), this stability is particularly important. It suggests that:

- The electricity–productivity relationship is not regime-dependent
- Structural breaks do not invalidate long-run inference
- ARDL estimates are policy-relevant and time-consistent.

4.4. Lag Selection Criteria (AIC/SBC)

The optimal lag length, selected on the basis of the AIC and SBC, is reported in Table 9.

The lag selection results indicate that lag 1 minimizes both AIC and SBC, suggesting an optimal parsimonious specification. This is consistent with small-sample time-series properties and avoids over-parameterization. Consequently, the ARDL model is estimated using P = 1, with optimal lag structures for regressors selected accordingly. The convergence of AIC and SBC strengthens the robustness of the chosen lag length.

The results of the ARDL bounds test for cointegration are presented in Table 10.

4.5. ARDL Bounds Test for Cointegration

The F-statistic of 6.412 exceeds the upper-bound critical value of 3.79, confirming the presence of a long-run cointegrating relationship. Economically, this indicates that productivity, electricity consumption, and power reliability are structurally linked over time. Deviations induced by outages or supply shocks are temporary, as the system gradually adjusts back toward equilibrium, implying that electricity is a foundational driver of Nigeria's productive capacity rather than a peripheral input.

4.6. Long-Run Estimates

The estimated long-run coefficients of the productivity model are reported in Table 11.

A 1% increase in electricity consumption raises productivity by 0.428%, confirming that energy deepens capital utilization and enhances production efficiency. In contrast, a 1% rise in transmission and distribution (T&D) losses (reflecting lower reliability) reduces productivity by 0.316%, showing that supply instability directly erodes output. Crucially, the reliability effect is about 74% as large as the consumption effect, implying that nearly three-quarters of energy's productivity gains can be offset by unreliability. The insight is that Nigeria's constraint is not only insufficient electricity generation, but also inefficient and unstable electricity delivery.

4.7. Error Correction Model (ECM)

The error-correction term, capturing the speed of adjustment to long-run equilibrium, is reported in Table 12.

The ECM coefficient of −0.641 implies that about 64.1% of any short-run deviation from longrun equilibrium is corrected each year. Economically, this corresponds to a full adjustment period of roughly 1.5 years, indicating that the system exhibits strong convergence dynamics toward its equilibrium path. However, repeated shocks, such as frequent power outages, can continuously push the economy away from equilibrium, offsetting the speed of adjustment. The insight is that Nigeria's productivity system is inherently resilient, but its performance is persistently undermined by unreliable electricity supply.

4.8. Short-Run Dynamics

The short-run dynamic estimates of the error-correction model are presented in Table 13.

The short-run elasticity of electricity consumption on productivity is 0.212, smaller than the long-run estimate of 0.428, indicating that productivity gains from higher energy use accumulate gradually over time. In contrast, the reliability shock of −0.287 is large and immediate, reflecting that power outages trigger instant production losses. This reveals a key asymmetry: electricity enhances productivity in a cumulative, long-run manner, while unreliability erodes it with immediate force. The insight is that, in the short run, power stability, not the sheer volume of energy, acts as the binding constraint on Nigeria's productive performance.

The direction of causality among the variables, based on the Toda–Yamamoto modified Wald (MWALD) test, is reported in Table 14.

4.9. Toda–Yamamoto Causality Results

The empirical results indicate a unidirectional causal relationship running from electricity consumption to productivity, with no evidence of reverse causality. Power unreliability also exerts a strong negative causal effect on productivity, reinforcing the idea that the quality of supply matters as much as the quantity. Importantly, the findings show that productivity does not drive electricity demand; instead, the prevailing energy-supply conditions, both in terms of availability and reliability, shape productivity outcomes. This pattern suggests that Nigeria

Table 10: Bounds test results

Statistic	Value	
F-statistic	**6.412**	
Critical Values (5%)	**I (0)**	**I (1)**
Pesaran et al. (2001)	2.62	3.79

Table 11: Long-run coefficients (dependent: ln (PROD))

Variable	Coefficient	t-Statistic	Prob.
ln (ELEC)	**0.428**	3.821	0.001
ln (REL)	**−0.316**	−3.224	0.004
ln (K)	0.147	2.070	0.048
ln (HC)	0.522	2.822	0.009
ln (INST)	0.201	2.421	0.022

Table 12: ECM result

Variable	Coefficient	t-Statistic	Prob.
ECM(-1)	**−0.641**	-5.432	0.000

Table 13: Short-run estimates

Variable	Coefficient	t-Statistic	Prob.
Δln (ELEC)	**0.212**	2.524	0.018
Δln (REL)	**−0.287**	−3.154	0.004
Δln (K)	0.082	1.673	0.106
Δln (HC)	0.301	2.263	0.031

Table 14: MWALD causality test

Direction	Chi-square	Prob.	Conclusion
ELEC → PROD	**8.214**	0.016	Causality
PROD → ELEC	2.103	0.349	No causality
REL → PROD	**9.531**	0.008	Causality
PROD → REL	1.887	0.389	No causality

operates under a supply-constrained energy regime rather than a demand-driven one, where firms and sectors are limited by the quantity and quality of power they can access rather than by their own demand-side dynamics.

The empirical evidence points to a coherent structural narrative: electricity consumption significantly enhances productivity, with an estimated elasticity of 0.428, while power unreliability imposes a substantial productivity penalty, quantified at −0.316. Adjustment toward the long-run equilibrium is relatively rapid, with roughly 64% of deviations corrected annually, yet recurrent reliability shocks prevent the full realization of these gains. Crucially, causality runs from energy conditions to productivity, not the other way around. The core finding is that expanding electricity consumption does raise productivity, but these gains are systematically undermined (both in the short run and over time) by persistent power unreliability. As a result, grid stability emerges as the dominant constraint on Nigeria's aggregate productive performance.

4.10. Additional Analyses and Robustness Extensions

To strengthen the empirical analysis and explore potential nonlinearities, the study extends the baseline ARDL framework along three dimensions. First, a Nonlinear ARDL (NARDL) specification (Shin et al., 2014) is estimated by decomposing electricity consumption and power reliability into positive and negative partial sums, enabling the detection of asymmetric effects where productivity gains from supply improvements may differ from losses due to deteriorations, an especially salient feature in Nigeria, where outage shocks are frequent and severe. Second, threshold effects are examined through a regimebased model in which the impact of electricity consumption on productivity depends on reliability levels, with preliminary evidence suggesting that beyond a critical T&D-loss threshold of about 20-25%, the marginal productivity of electricity declines sharply, pointing to nonlinear reliability constraints. Third, a sectoral decomposition disaggregates productivity into industrial and service components, revealing that industrial productivity is markedly more sensitive to reliability shocks, consistent with higher energy intensity and lower substitutability than services.

4.11. Nonlinear ARDL (NARDL) Specification

To capture asymmetry, electricity consumption and reliability are decomposed into positive and negative partial sums:

$$ELEC_t^{+} = \sum_{j=1}^{t} \max(\Delta ELEC_j, 0), ELEC_t^{-} = \sum_{j=1}^{t} \min(\Delta ELEC_j, 0) \tag{4}$$

$$REL_t^{+} = \sum_{j=1}^{t} \max(\Delta REL_j, 0), REL_t^{-} = \sum_{j=1}^{t} \min(\Delta REL_j, 0) \tag{5}$$

4.12. NARDL Long-Run Model

$$\ln(PROD_t) = \alpha_0 + \alpha_1 \ln(ELEC_t^{+}) + \alpha_2 \ln(ELEC_t^{-}) + \alpha_3 \ln(REL_t^{+}) + \alpha_4 \ln(REL_t^{-}) + X_t^{'}\gamma + \varepsilon_t \tag{6}$$

Where:

- REL^{+}: Worsening reliability (increase in losses)
- REL^{-}: Improvement in reliability
- X_t: Controls (K, HC, INST).

The asymmetric long-run estimates from the nonlinear ARDL specification are reported in Table 15.

Positive shocks to electricity consumption raise productivity by 0.462, more than double the 0.191 effect of negative shocks, indicating that energy expansion drives productivity strongly while contractions have a comparatively muted impact. In contrast, deteriorations in reliability reduce productivity by 0.372, significantly more than the 0.148 gain from reliability improvements, showing that losses hurt far more than gains help. The core asymmetry is that productivity is highly sensitive to negative reliability shocks, confirming that power outages impose substantial, nonlinear economic damage on Nigeria's productive performance.

4.13. Threshold Regression (Reliability Regime Effects)

To test nonlinear constraints, a threshold model is estimated:

$$\ln(PROD_t) = \begin{cases} \beta_1 \ln(ELEC_t) + X_t^{'}\delta + \varepsilon_t, & REL_t \le \tau \\ \beta_2 \ln(ELEC_t) + X_t^{'}\delta + \varepsilon_t, & REL_t > \tau \end{cases} \tag{7}$$

Where:

- τ = estimated threshold level of T&D losses.

4.14. Estimated Threshold

The regime-specific estimates from the threshold regression are reported in Table 16.

τ = 22.4% (T&D losses).

When power reliability is acceptable (defined as T&D losses at or below 22.4%) electricity consumption strongly boosts productivity, with an elasticity of 0.517. However, when reliability deteriorates beyond this threshold, the elasticity falls to 0.173, becoming weak and only borderline significant. The implication is that beyond a critical reliability threshold, electricity loses much of its productivity-enhancing power, highlighting that grid stability is a necessary precondition for energy to translate into meaningful output gains.

Table 15: NARDL long-run results

Variable	Coefficient	t-Stat	Prob.
$\ln(ELEC^{+})$	**0.462**	3.944	0.001
$\ln(ELEC^{-})$	**0.191**	2.117	0.043
$\ln(REL^{+})$	**−0.372**	−3.551	0.002
$\ln(REL^{-})$	**−0.148**	−1.982	0.058

Table 16: Threshold regression results

Regime	ELEC coefficient	t-Stat	Prob.
Low-loss regime (REL ≤22.4%)	**0.517**	4.221	0.000
High-loss regime (REL >22.4%)	**0.173**	1.892	0.067

Combining the ARDL, NARDL, and threshold results reveals that, linearly, electricity consumption raises productivity by 0.428, yet this effect is asymmetric and fragile: positive shocks have a stronger impact than negative ones, and gains are sharply eroded by reliability deterioration. The threshold analysis further shows that productivity gains from electricity collapse when reliability falls below a critical level, indicating that powersupply instability truncates the benefits of energy expansion. The final economic conclusion is that Nigeria's productivity is constrained not only by the quantity of electricity but by a nonlinear reliability regime, where supply instability simultaneously amplifies losses and undermines gains, rendering additional energy inputs ineffective beyond critical thresholds of system inefficiency.

5. DISCUSSION OF FINDINGS

The empirical results provide strong support for the energy-led productivity hypothesis while substantially refining its interpretation within the Nigerian context. The positive and significant long-run elasticity of electricity consumption (0.428) aligns with prior evidence that energy is a critical production input (Adenikinju, 1998; Shahbaz et al., 2013; Gold et al., 2024). However, this study advances the literature by demonstrating that the productivity gains from electricity are conditional on supply reliability, thereby resolving inconsistencies in earlier Nigerian studies that reported mixed or unstable coefficients (Akinlo, 2009; Olayemi, 2012). Consistent with Andersen and Dalgaard (2013), the negative and significant impact of power unreliability (−0.316) confirms that outages impose substantial productivity penalties, but the magnitude observed here indicates that reliability is not merely a constraint, it is a co-determinant of productive efficiency.

Nigeria-specific structural dynamics provide a compelling explanation for these findings. Chronic grid instability has entrenched widespread dependence on self-generation, with firms relying heavily on diesel and petrol generators as a substitute for unreliable public supply (Adenikinju, 2005; Iroh et al., 2022). This coping mechanism, while mitigating outright production stoppages, significantly inflates marginal costs and reduces overall efficiency, effectively acting as a distortionary tax on productive activity. The short-run results reinforce this mechanism: while electricity consumption improves productivity gradually, reliability shocks exert immediate and disproportionately large negative effects (−0.287), reflecting unplanned downtime, equipment damage, and production disruptions. This asymmetry is further corroborated by the NARDL results, where negative reliability shocks have a stronger impact than improvements, indicating that the economic costs of outages are nonlinear and persist beyond the duration of the shock.

The threshold analysis deepens this insight by identifying a critical reliability regime: once transmission and distribution losses exceed approximately 22.4%, the marginal productivity of electricity collapses. This finding is particularly salient for Nigeria, where loss levels frequently exceed this threshold, implying that incremental increases in electricity supply may yield diminishing or negligible productivity gains under prevailing system inefficiencies. This result helps reconcile why expansions in installed capacity and electricity access have not translated into sustained productivity improvements, a puzzle highlighted in the stylized facts and broader literature (World Bank, 2020).

Importantly, the causality results reveal a unidirectional relationship from electricity consumption and reliability to productivity, contradicting the feedback hypothesis found in some cross-country studies (Wolde-Rufael, 2006). This suggests that Nigeria operates within a supply-constrained energy regime, where firms' productive capacity is fundamentally limited by the availability and quality of electricity rather than endogenous demand dynamics. No major unexpected results emerge; rather, the findings systematically clarify previously ambiguous relationships by explicitly incorporating reliability into the empirical framework.

Overall, the results establish that electricity consumption alone is insufficient to drive productivity in Nigeria. Instead, reliability is the binding constraint, shaping both the magnitude and sustainability of energy-induced productivity gains.

6. CONCLUSION AND POLICY IMPLICATIONS

This study provides robust evidence that electricity consumption and power reliability jointly determine productivity dynamics in Nigeria. The results confirm a stable long-run relationship, with electricity consumption exerting a positive elasticity (0.428) and power unreliability imposing a substantial negative effect (−0.316), while causality runs unidirectionally from energy conditions to productivity. Crucially, nonlinear and threshold analyses reveal that productivity gains from electricity are fragile and collapse under poor reliability regimes, establishing grid stability as the binding constraint. The study contributes to the literature by explicitly disentangling electricity access from reliability and by integrating ARDL with Toda–Yamamoto causality to resolve long-standing ambiguities in the energy–productivity nexus.

Notwithstanding these contributions, limitations remain. The use of T&D losses as a proxy may not fully capture outage duration or firm-level disruptions, while annual data constrain high-frequency dynamics. Methodologically, linear ARDL assumptions may still mask deeper structural breaks. Future research should incorporate firm-level datasets, alternative reliability metrics (e.g., SAIDI/SAIFI), and explore panel or structural models to better capture sectoral heterogeneity and dynamic adjustment mechanisms.

The findings necessitate a decisive shift in Nigeria's electricity policy from expanding access to ensuring reliability, as productivity gains from electricity consumption (0.428) are substantially eroded by unreliability (−0.316). First, investment priorities must target grid stability, particularly transmission expansion, real-time system management, and loss reduction below the identified 22% threshold, beyond which electricity loses productivity effectiveness. Second, regulatory reforms should move beyond tariff adjustments to enforce performance-based regulation for DisCos, tying revenue recovery to measurable reductions in T&D and ATC&C losses. Third, given widespread generator dependence, policy should incentivize firm-level energy efficiency and captive renewable adoption (e.g., embedded solar-hybrid systems) through tax credits and concessional financing, reducing reliance on costly diesel generation. Finally, coordinated sector governance, linking gas supply, transmission upgrades, and distribution efficiency, is critical to eliminate structural bottlenecks. The central implication is clear: reliability, not capacity expansion alone, is the binding constraint on productivity in Nigeria's energy–economy nexus.

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