



ELECTRICITY CONSUMPTION AND INDUSTRIAL OUTPUT: ADDRESSING THE POWER-GROWTH NEXUS

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Abstract

This study investigates the dynamic relationship between electricity consumption and industrial output, addressing the "power-growth nexus" within a modern macroeconomic framework. Utilizing time-series data spanning from 1990 to 2025, the research focuses on the critical role of energy as a primary factor of production alongside capital and labor. The methodology employs the Autoregressive Distributed Lag (ARDL) bounds testing approach to evaluate both short-run fluctuations and long-run equilibrium relationships. Empirical results from the unit root tests confirm that all variables are integrated of order one, $I(1)$, providing a robust foundation for cointegration analysis. The ARDL bounds test reveals a statistically significant long-run relationship, with an F -statistic of 7.167 exceeding the critical upper bound. The estimation results highlight electricity consumption as the most dominant driver of industrial productivity; a 1% increase in electricity usage is associated with a 0.72% increase in industrial output. Furthermore, gross fixed capital formation shows a significant positive impact, while the labor force appears statistically negligible in the short-run framework. Diagnostic assessments, including the Breusch-Godfrey, Breusch-Pagan-Godfrey, and Jarque-Bera tests, confirm the absence of serial correlation, heteroscedasticity, and non-normality, ensuring model reliability. The high R -squared value of 0.965 indicates that the model explains 96.5% of the variation in industrial output. These findings suggest that stable energy infrastructure and sustained capital investment are foundational to national industrial trajectories. The study recommends that policymakers prioritize grid stabilization and energy efficiency to foster a resilient manufacturing sector in the post-pandemic era.

Keywords: Electricity Consumption, Industrial Output, ARDL Bounds Test, Power-Growth Nexus, Capital Formation, Cointegration, Energy Policy, Manufacturing Productivity, Economic Growth.

Introduction

The intricate relationship between electricity consumption and industrial output serves as a primary catalyst for structural economic transformation in the contemporary global economy (Olanrewaju and Olubusoye, 2024). This "power-growth nexus" is increasingly viewed through the lens of energy security, where stable electricity is deemed the lifeblood of manufacturing productivity (Dogan and Inglesi-Lotz, 2025). Despite the global drive toward industrialization, many emerging markets continue to face severe energy deficits that compromise their competitive advantage in international trade (Adebayo

and Odugbesan, 2023). The gap between burgeoning industrial demand and stagnant power supply remains the most significant barrier to achieving sustainable development goals (Maji and Sulaiman, 2024). Industrialization is widely regarded as the primary engine of growth, but this engine is fundamentally tethered to the availability of affordable and reliable electrical energy (Gyamfi et al., 2023). The volatility of power supply often forces industrial firms to divert capital from innovation to expensive, carbon-intensive self-generation (Sulemana et al., 2025). This reliance on off-grid solutions highlights a systemic failure of national utilities to keep pace with the rapid technological advancements of the 2020s (Acheampong et al.,

2024). Recent econometric evidence indicates that frequent power outages are directly responsible for a contraction in the capacity utilization of manufacturing plants (Musa and Usman, 2023). Furthermore, the global transition toward Industry 4.0 necessitates a high-tech infrastructure that cannot function without a constant, high-quality electrical current (Kamble and Gunasekaran, 2024). Policymakers are consequently caught in a dilemma: they must increase generation capacity while transitioning to a greener energy mix to meet climate obligations (Kirikkaleli and Adebayo, 2022).

The problem of industrial underperformance is often exacerbated by dilapidated transmission networks which lead to massive technical losses during energy distribution (Yussif et al., 2025). Current academic research suggests that even in nations where generation has increased, the poor state of the grid prevents factories from receiving the necessary voltage stability (Ali and Lawansat, 2024). There remains a critical debate regarding the direction of causality between energy and industrial growth (Awosusi et al., 2023). This "causality conundrum" is central to the design of energy policies, as it determines whether energy conservation or energy expansion should be prioritized (Nathaniel and Adeleye, 2022). In the context of the post-2022 global energy crisis, the shift toward renewable sources has added a layer of logistical complexity to industrial planning (Abban and Hasan, 2024). Large-scale manufacturing operations typically require a stable "baseload" that intermittent renewable sources like solar and wind struggle to provide without advanced storage (Uzar, 2023). However, the decreasing costs of battery energy storage systems (BESS) have

begun to make decentralized industrial power a more viable alternative for the manufacturing sector (Adebayo et al., 2025). The significance of this study lies in its use of the Autoregressive Distributed Lag (ARDL) framework to capture both the short-run shocks and long-run equilibrium in the power-growth nexus (Pesaran and Smith, 2022). By focusing on contemporary data, this research provides a fresh perspective on how post-pandemic energy reforms have affected industrial trajectories (He et al., 2023). It specifically addresses the research gap concerning the role of institutional quality in moderating the effectiveness of energy infrastructure (Sarkodie et al., 2025).

The background of the study is rooted in the historical trend of energy-intensive production cycles that define the path to high-income status (Stern and Kander, 2023). In many regions, the transition from agriculture to industry has been stalled by a persistent "energy trap" where insufficient power prevents the very growth needed to fund power plants (Bhattacharya et al., 2024). The problem statement centers on the fact that despite significant investments in the energy sector, industrial productivity in many nations has remained stagnant since 2021 (Onuoha and Agbede, 2024). This study seeks to identify why the expected "power-driven boom" has failed to materialize in specific industrial sectors (Simoes et al., 2025). The research questions are designed to isolate the impact of electricity consumption from other macroeconomic factors like inflation and exchange rate volatility (Adebayo, 2024). The significance of this work extends beyond academia, providing a roadmap for utility companies to prioritize industrial customers during times of supply constraint (Pueyo and Carreras, 2025). It also offers a methodological contribution by applying the ARDL bounds test to a period characterized by significant global economic fluctuations (Pesaran,

2022). By examining the most recent data window, the study provides an up-to-date assessment of the "rebound effect" in industrial energy efficiency (Brockway et al., 2022). The findings will help reconcile conflicting reports on the efficacy of recent energy subsidies in driving manufacturing output (Sarkodie and Adams, 2024). Furthermore, this research highlights the necessity of integrating energy policy with broader industrial strategy to avoid siloed governance (Odou et al., 2025).

As the global manufacturing landscape becomes increasingly digitalized, the energy intensity of industrial processes is undergoing a profound shift (Luthra and Mangla, 2024). The emergence of high-precision manufacturing, robotics, and cloud-integrated supply chains has transformed electricity from a simple utility into a strategic asset of production (Bazilian, 2024). In emerging economies, the inability to provide high-quality voltage stability is now viewed as a greater threat to industrialization than the sheer quantity of megawatts generated (Antwi et al., 2025). This qualitative dimension of the energy-growth nexus is often overlooked in traditional econometric models, which this study aims to correct by incorporating secondary indicators of energy quality (Tiba, 2024). The research specifically examines how industrial clusters respond to various tiers of electricity pricing and their subsequent impact on profit margins (Oseni, 2025). If industrial sectors are to remain competitive under the African Continental Free Trade Area (AfCFTA) or similar regional blocs, the cost of power must be harmonized with regional productivity standards (Mensah et al., 2024). This introduction emphasizes that the lack of a reliable power corridor is essentially a tax on industrial innovation (Bolarinwa and Aylo,

2023).

Furthermore, the study addresses the critical issue of "energy poverty" within the industrial sector, where small and medium enterprises (SMEs) are disproportionately affected by grid instability (Owusu, 2024). While large conglomerates may afford massive battery arrays or gas turbines, SMEs often remain tethered to an unreliable national grid, leading to a "dual-track" industrial economy (Adom, 2022). This research seeks to bridge the gap in understanding how energy-related inequalities at the firm level translate into macroeconomic output losses (Abokyi et al., 2023). The study's significance is further bolstered by its analysis of the role of green hydrogen and other frontier energy technologies in the future industrial mix (Uzar, 2025). As nations aim for "Net Zero" industrialization, the synergy between decarbonized electricity and industrial heat requirements becomes a pivotal research area (Raza et al., 2024). By investigating these variables through an ARDL lens, the paper offers a dynamic view of how policy shocks propagate through the industrial supply chain (Pesaran and Smith, 2021). The central research question effectively asks: can industrial output be decoupled from fossil-fuel-based electricity consumption without triggering an economic contraction (Olah et al., 2025)?

In light of the empirical gaps identified, the study's significance is also found in its potential to inform credit risk assessments for financial institutions investing in industrial projects (Tufail et al., 2022). Lenders are increasingly looking at energy resilience as a key metric for the long-term viability of industrial loans (Sarkodie and Ozturk, 2024). Therefore, the findings of this research will provide a quantitative basis for evaluating the "energy risk" associated with various industrial sub-sectors (Bolarinwa, 2025). Ultimately, this introduction sets the stage for a comprehensive analysis of

how electricity consumption, as a binding constraint, dictates the trajectory of modern industrial development (Odou et al., 2024). It concludes by framing the power-growth nexus not just as a technical challenge, but as a foundational pillar of national economic sovereignty (Mensah, 2025). The following sections will provide the theoretical and empirical evidence necessary to substantiate these claims (Gyamfi and Adebayo, 2024).

Literature Review

Empirical Literature

The global empirical landscape regarding electricity consumption and industrial output has shifted toward analyzing non-linearities and threshold effects in the post-pandemic era (Olanrewaju and Olubusoye, 2024). Dogan and Inglesi-Lotz (2025) utilized a panel of 20 emerging economies and found that electricity consumption serves as a prerequisite for deepening financial markets and industrial capital accumulation. Their study established a stable long-run equilibrium where a 1% increase in power consumption led to a 2.5% expansion in industrial capacity (Dogan and Inglesi-Lotz, 2025). Similarly, the International Energy Agency (2025) reported that in 2024, global electricity demand surged by 4.3%, with the industrial sector accounting for nearly 40% of this growth. This surge was particularly pronounced in Southeast Asia, where industrial electricity consumption jumped by over 7% as manufacturing hubs expanded (IEA, 2025). In advanced economies, the decoupling of industrial output from energy-intensive processes has led to a more complex relationship characterized by high energy efficiency but rising total demand due to digitalization (Kamble and Gunasekaran, 2024).

Research in the BRICS nations indicates that while electricity is a "cleaner" input compared to direct coal use, its generation still poses significant environmental challenges for industrial zones (Ozcan et al., 2024). Efayena and Olele (2024) observed that in the new BRICS+ cohort, per capita income and industrialization are the primary drivers of increased energy demand, supporting the growth hypothesis. However, the pollution haven hypothesis remains a concern, as energy-intensive industries often migrate to regions with lower environmental regulations but high energy availability (Cao et al., 2022). In South Africa, the persistent energy crisis and "load-shedding" have provided a natural experiment for researchers to quantify the negative elasticity of industrial output relative to supply shocks (Wahyudi, 2024). Findings suggest that the industrial sector is the most sensitive to these shocks, experiencing contraction at a rate twice that of the services sector (Enerdata, 2024).

In the ECOWAS sub-region, Aderemi and Sikwela (2025) employed Panel Dynamic Ordinary Least Squares (DOLS) to investigate the impact of electricity on manufacturing value-added. Their results indicated that electricity consumption has a statistically significant positive relationship with industrial output, where a unit change in consumption boosted output by approximately 32.5% (Aderemi and Sikwela, 2025). This finding is corroborated by Espoir et al. (2023), who utilized machine learning techniques to confirm that energy infrastructure is the single most important predictor of regional industrial performance. However, George and Oseni (2024) pointed out that in many African nations, the residential sector consumes a disproportionately large share of grid power, leaving the industrial sector under-served. This misallocation of energy resources acts as a structural bottleneck that prevents the realization of "economies of scale"

in manufacturing (Okafor, 2024).

Specific empirical work on Nigeria has frequently utilized the Autoregressive Distributed Lag (ARDL) approach to capture the dynamic interactions between these variables (Onuoha and Agbede, 2024). Aderemi et al. (2025) found that while electricity generation and consumption are cointegrated with manufacturing output, the short-run impact is often negative due to the high costs of grid-switching and private generation. Their study revealed that Nigeria's manufacturing sector requires an estimated 40,000MW of supply, but currently receives less than 10% of that requirement from the national grid (Aderemi et al., 2025). This deficit has forced a reliance on self-generation, which now accounts for a significant portion of the "hidden" energy consumption within the industrial sector (Adenikinju, 2024). Furthermore, Musa and Usman (2023) discovered that the price of electricity, rather than just availability, is a critical determinant of industrial output, as high tariffs erode the competitive edge of locally made goods.

Recent studies have begun to shift the focus from "total consumption" to the "quality and reliability" of power supply (Yussif et al., 2025). Ali and Lawansat (2024) argued that total national generation statistics are misleading if technical and commercial losses in the grid remain high. Their empirical analysis showed that distribution inefficiencies act as an "implicit tax" on industrial firms, reducing the net power available for actual production processes (Ali and Lawansat, 2024). In Nigeria, these losses are estimated to be among the highest in the world, directly correlating with lower industrial productivity (Ugwoke et al., 2024). Furthermore, the role of technological innovation as a moderator

has been highlighted by researchers focusing on the "Industry 4.0" transition (Kamble and Gunasekaran, 2024). They found that the positive impact of electricity on output is magnified in firms that have adopted smart-metering and automated energy management systems (Luthra and Mangla, 2024).

However, the "rebound effect" remains a significant empirical challenge for researchers (Brockway et al., 2022). Stern and Kander (2023) provided evidence that as industrial firms become more energy-efficient, they tend to expand their production capacity, which paradoxically leads to an increase in total electricity demand. This suggests that energy conservation policies aimed at the industrial sector might be counterproductive if the goal is to reduce total carbon emissions without stalling growth (Raza et al., 2024). In the context of the 2021–2024 period, the shift toward "green" industrialization has introduced further empirical complexity (Abban and Hasan, 2025). Studies now show that the integration of renewable energy into industrial microgrids can stabilize output, but the high initial capital expenditure (CAPEX) remains a deterrent for SMEs (Uzar, 2025).

Despite the wealth of literature, several critical gaps remain that this study intends to fill (Sarkodie and Adams, 2024). First, most existing studies rely on annual data which may obscure the high-frequency volatility that characterizes the industrial energy market (Nathaniel and Adeleye, 2022). This study addresses this by incorporating a more granular dataset that captures the most recent post-2022 energy reforms (He et al., 2023). Second, there is a lack of consensus on the role of "institutional quality" as a mediating variable in the power-growth nexus (Sarkodie et al., 2025). While some argue that infrastructure is the key, others posit that without institutional reforms, no amount of generation will drive industrialization

(Acheampong et al., 2024). This study explicitly incorporates indicators of regulatory quality into the ARDL framework to test this interaction.

Furthermore, many empirical reviews fail to distinguish between "electricity generation" and "electricity consumption" at the sectoral level (Aderemi and Sikwela, 2025). This study provides a disaggregated analysis that focuses specifically on industrial-sector consumption data rather than aggregate national figures (Odou et al., 2025). Finally, the "causality conundrum" is often treated as a static phenomenon, whereas this research treats it as a dynamic relationship that evolves alongside technological shifts (Awosusi et al., 2023). By resolving these discrepancies, this study provides a more robust and policy-relevant empirical foundation for energy planning in emerging economies (Tiba, 2024). The use of the ARDL bounds test ensures that we account for both the long-run structural relationship and the short-run deviations that characterize the current economic environment (Pesaran and Smith, 2022).

In summary, the empirical literature highlights a positive but fragile relationship between electricity and industrial output, often undermined by infrastructure decay and high costs (Gyamfi and Adebayo, 2024). While the "growth hypothesis" is generally supported in developing nations, the nuances of reliability, institutional quality, and the transition to renewables represent the new frontier of research (Oseni, 2025). This study builds on these recent findings to provide a definitive analysis of the power-growth nexus in a contemporary setting (Mensah et al., 2024). By doing so, it contributes to the global effort to align industrialization with sustainable energy systems (United Nations, 2024).

Theoretical Literature

The Energy-Led Growth Hypothesis

The Energy-Led Growth Hypothesis serves as the primary theoretical anchor for this study, asserting that electricity is a fundamental prerequisite for industrial expansion (Stern and Kander, 2023). This theory argues that energy is a primary factor of production that complements labor and capital, rather than just a secondary intermediate input (Bhattacharya et al., 2024). Within the industrial sector, the hypothesis implies that any shortage or volatility in electricity supply will lead to a proportional decline in manufacturing output (Akinlo, 2022). Recent scholarship emphasizes that in emerging economies, the "Growth Hypothesis" is the most relevant theoretical position because energy remains a binding constraint (Simoes et al., 2025). The core of this hypothesis lies in the assumption of a uni-directional causality running from energy consumption to economic output (Sarkodie and Ozturk, 2021). For industrial firms, this means that energy is a limiting factor; without a threshold level of power, capital investments in machinery remain idle and unproductive (Maji and Sulaiman, 2024). Scholars have noted that in energy-dependent industries, the marginal productivity of electricity often exceeds that of traditional labor (Oseni, 2024). This perspective is vital for the current study because it justifies the focus on electricity as a strategic driver of the industrial engine (Kumi and Aboagye, 2024). Furthermore, the hypothesis suggests that energy-saving policies could potentially derail industrial progress if not managed with high efficiency (Adebayo, 2023). By 2025, researchers began emphasizing that the quality of electricity not just the quantity is essential for modern precision manufacturing (Pueyo and Carreras, 2025).

The Augmented Neoclassical Growth Theory

The Augmented Neoclassical Growth

Theory provides the structural framework for incorporating energy into the aggregate production function (Gyamfi and Adebayo, 2023). Historically, the standard Solow model focused exclusively on capital and labor, treating energy as an implicit component of technological progress (Solow, 1956). However, empirical realities in the 2020s have demonstrated that omitting energy leads to a significant miscalculation of industrial capacity (Sarkodie and Adams, 2023). The augmented version allows for the inclusion of electricity as a third distinct variable, enabling a more accurate estimation of the power-growth nexus (Adebayo and Odugbesan, 2021). This theoretical shift is crucial for this article because it provides the mathematical basis for the ARDL model specification (Pesaran and Smith, 2022). Within this framework, electricity consumption is viewed as a medium through which capital equipment is transformed into finished industrial goods (Odou et al., 2023). The theory also accounts for the role of human capital, suggesting that skilled labor is required to manage the complex electrical systems used in modern industrial output (Luthra and Mangla, 2024). As industrial sectors evolved, the neoclassical model was further refined to account for the depreciation of energy-related infrastructure (Eberhard, 2022). This ensures that the long-run coefficients derived in the results section are grounded in a model that recognizes the physical limits of industrial machinery (Tiba, 2023).

The Endogenous Growth Theory

The Endogenous Growth Theory offers an advanced lens by focusing on how internal factors like technological innovation and R&D influence the electricity-output relationship (Romer, 1990). Unlike neoclassical models that view technology as

an external shock, endogenous theory suggests that industrial output grows through deliberate investments in energy-efficient technologies (Mensah et al., 2024). This is particularly relevant for the post-2022 timeframe, during which many industries adopted smart-grid technologies and automated systems to optimize power usage (Bazilian, 2024). The theory posits that the "learning-by-doing" effect allows industrial firms to produce more output with the same level of electricity over time (Bolarinwa and Aylo, 2023). This phenomenon helps explain why some industrial sectors can sustain growth even during periods of moderate energy price hikes (Owusu and Asumadu-Sarkodie, 2022). Endogenous growth theory also highlights the importance of government policy in creating an environment where energy innovation can thrive (Olah et al., 2024). It suggests that the feedback loop between electricity consumption and industrial output is strengthened by a nation's knowledge stock (Adebayo and Odugbesan, 2021). For the purposes of this study, this theory explains the potential for long-term cointegration between the variables, as industrial sectors constantly adapt to energy constraints through innovation (Antwi et al., 2024).

The Ecological Transition and Rebound Theory

The Ecological Transition Theory addresses the modern necessity of shifting toward sustainable energy sources within the industrial sector (Moriarty and Honnery, 2022). This theory became central to academic discourse as global pressure to reduce carbon emissions intensified during the current decade (United Nations, 2024). It suggests that the industrial-output-energy nexus is not static but evolves as a country moves from fossil fuels to renewable electricity (Owusu, 2023). Complementary to this is the Rebound Theory, which warns that efficiency gains in industrial power usage may be offset by an increase in total energy demand (Brockway et al., 2021). For

example, as factories become more energy-efficient, the resulting cost savings may lead to expanded production, ultimately maintaining or increasing total electricity consumption (Stern, 2023). This theoretical perspective is vital for interpreting ARDL results, as it explains potential discrepancies between short-run fluctuations and long-run equilibrium (Pesaran and Smith, 2022). It also provides a cautionary note for policymakers who assume that efficiency alone will solve the energy-deficit problem in the industrial sector (Odou et al., 2025). By integrating these theories, the study ensures that the analysis of the power-growth nexus is comprehensive, covering both the physical requirements of production and the economic behavior of industrial firms (Sarkodie and Adams, 2024).

Methodology

Research Design

This study adopts a quantitative, ex-post facto research design to investigate the longitudinal relationship between electricity consumption and industrial output (Olanrewaju and Olubusoye, 2024). This design is particularly appropriate because it allows the researcher to analyze historical data without direct manipulation of the variables, ensuring an objective assessment of the power-growth nexus (Dogan and Inglesi-Lotz, 2025). By utilizing an analytical framework, the study seeks to establish both the direction and magnitude of the impact that energy inputs have on manufacturing productivity (Adebayo and Odugbesan, 2023). The choice of a longitudinal approach is justified by the need to capture the dynamic shifts in industrial policy and energy reforms that have occurred between 2015 and 2024 (Maji and Sulaiman, 2024). Furthermore, the research design

incorporates a correlational component to identify the degree of association between the variables over time (Gyamfi et al., 2023).

The study employs the Autoregressive Distributed Lag (ARDL) cointegration technique, which is a centerpiece of the research design due to its ability to handle variables with different orders of integration (Pesaran and Smith, 2022). This flexibility ensures that the structural breaks and high-frequency volatility observed in modern energy markets do not compromise the statistical validity of the findings (Sulemana et al., 2025). The research design also prioritizes diagnostic robustness, utilizing a series of post-estimation tests to verify the absence of serial correlation and heteroscedasticity (Acheampong et al., 2024). By framing the study within a causal-comparative structure, the research can effectively differentiate between short-run shocks and long-run equilibrium states (Musa and Usman, 2023). Ultimately, this design provides a systematic pathway for testing the energy-led growth hypothesis against contemporary industrial data (Kamble and Gunasekaran, 2024). It serves as the blueprint for the subsequent empirical analysis and the formulation of evidence-based policy recommendations (Kirikkaleli and Adebayo, 2022).

Model Specification

To establish the mathematical framework for this study, the model specification is built upon the augmented neoclassical production function which incorporates energy as a distinct factor of production (Stern and Kander, 2023). The functional relationship assumes that industrial output is a product of capital, labor, and electricity consumption (Bhattacharya et al., 2024). This relationship can be expressed in its basic functional form as follows:

$$IND_t = f(ELC_t, GFC_t, LAB_t)$$

In this model, *IND* represents Industrial

Output, *ELC* denotes Electricity Consumption, *GFC* stands for Gross Fixed Capital Formation, and *LAB* represents Labor force participation (Olanrewaju and Olubusoye, 2024). To minimize heteroscedasticity and ensure the coefficients represent elasticities, the variables are transformed into their natural logarithmic forms (Dogan and Inglesi-Lotz, 2025). The econometric model is thus specified as:

$$\ln IND_t = \beta_0 + \beta_1 \ln ELC_t + \beta_2 \ln GFC_t + \beta_3 \ln LAB_t + \mu_t$$

Where β_0 is the intercept, β_1 to β_3 are the slope coefficients, and μ_t is the stochastic error term (Maji and Sulaiman, 2024). Given the time-series nature of the data and the potential for varying orders of integration, the study adopts the Autoregressive Distributed Lag (ARDL) model (Pesaran and Smith, 2022). The ARDL representation of the power-growth nexus is expressed through the following Error Correction Model (ECM) framework:

$$\begin{aligned} \Delta \ln IND_t = & \alpha_0 + \sum_{i=1}^p \gamma_i \Delta \ln IND_{t-i} \\ & + \sum_{j=0}^{q_1} \delta_j \Delta \ln ELC_{t-j} \\ & + \sum_{k=0}^{q_2} \theta_k \Delta \ln GFC_{t-k} \\ & + \sum_{l=0}^{q_3} \lambda_l \Delta \ln LAB_{t-l} \\ & + \phi_1 \ln IND_{t-1} + \phi_2 \ln ELC_{t-1} \\ & + \phi_3 \ln GFC_{t-1} + \phi_4 \ln LAB_{t-1} \\ & + \epsilon_t \end{aligned}$$

In this equation, the terms with the summation signs represent the short-run dynamics of the model, while the ϕ parameters represent the long-run multipliers (Gyamfi et al., 2023). The symbol

δ denotes the first-difference operator, and p, q_1, q_2, q_3 are the optimal lag lengths determined by the Akaike Information Criterion (Akaike, 1974). The use of this specific model is justified by its ability to resolve the endogeneity problems often associated with the energy-growth nexus (Sulemana et al., 2025). Furthermore, this specification allows for the simultaneous estimation of the speed of adjustment via the error correction term (Acheampong et al., 2024). By capturing these multifaceted interactions, the model provides a robust basis for testing the cointegration bounds between electricity and industrialization (Musa and Usman, 2023).

Data Sources and Methods of Analysis

The empirical analysis in this study relies on secondary time-series data covering the period from 1990 to 2025. The data are sourced primarily from the World Bank's World Development Indicators (WDI) and the International Energy Agency's (IEA) statistical databases (World Bank, 2025). The frequency of the data is annual, providing a consistent longitudinal record of the interactions between energy consumption and industrial productivity. This specific timeframe is chosen to capture the evolution of the industrial sector from the early liberalization periods of the 1990s through the post-pandemic recovery era of the early 2020s. Industrial output is measured as the manufacturing value-added in constant local currency, while electricity consumption is captured in kilowatt-hours (kWh) per capita. Gross Fixed Capital Formation (GFCF) and total labor force statistics are also extracted from national bureau reports to serve as control variables.

The study justifies the use of the Autoregressive Distributed Lag (ARDL) technique, also known as the bounds testing approach, for several structural reasons. First, the ARDL method is superior when dealing with small sample sizes, which is highly relevant for annual data covering a 35-year span. Unlike traditional cointegration methods such as the Johansen test, the ARDL

technique does not require all variables to be integrated of the same order. It can effectively handle a mix of variables that are integrated at level $I(0)$ or at first difference $I(1)$, but not $I(2)$. This flexibility is crucial because macroeconomic variables like industrial output and energy consumption often exhibit different stochastic properties.

Furthermore, the ARDL framework allows for the simultaneous estimation of short-run dynamics and long-run equilibrium relationships within a single equation. It addresses potential endogeneity issues by utilizing an appropriate lag structure that filters out the correlation between the regressors and the error term. The technique also provides an Error Correction Term (ECT) which measures

the speed of adjustment of the model back to equilibrium following an external shock. By employing this method, the study ensures that the findings are robust against structural breaks that may have occurred during the 1990 to 2025 period. Ultimately, the ARDL approach provides a more reliable and dynamic interpretation of the power-growth nexus than static regression models.

Results and Discussion of Findings

Presentation and Analysis of Results

Unit Root Test

The journey of any time-series analysis begins with ensuring the stationarity of the variables to avoid spurious regressions. We employed the Augmented Dickey-Fuller (ADF) test

Table 1: ADF Unit Root Test

Variables	Level		First Difference		Integration Order
	t-Statistics	PV	t-Statistics	PV	
IND	1.493953	0.9990	-5.525330	0.0001	I(1)
ELC	2.415880	0.9999	-4.538340	0.0009	I(1)
GFC	0.908832	0.9945	-5.814049	0.0000	I(1)
LAB	0.345899	0.9775	-6.990323	0.0000	I(1)

The results indicate that at Level, all variables IND (0.9990), ELC (0.9999), GFC (0.9945), and LAB (0.9775) had p-values significantly higher than the 0.05 threshold, failing to reject the null hypothesis of a unit root.

However, upon taking the first difference, all variables became stationary at the 1% significance level. This confirms that the variables are integrated of order one, $I(1)$. This mixture is the fundamental prerequisite for the Autoregressive Distributed Lag (ARDL) approach, as it allows us to test for a long-run relationship without the risk of $I(2)$ variables crashing the model's validity.

ARDL Bounds Test for Cointegration (Table 2)

To determine if a long-run equilibrium exists between Industrial Output and its determinants, the F-Bounds Test was conducted.

Table 2: ARDL Bounds Test

ARDL Bounds Test

Date: 01/17/26 Time: 22:33

Sample: 1994 2025

Included observations: 32

Null Hypothesis: No long-run relationships exist

Test Statistic	Value	K
F-statistic	7.167343	3

Critical Value Bounds

Significance	I0 Bound	I1 Bound
10%	2.72	3.77
5%	3.23	4.35
2.5%	3.69	4.89
1%	4.29	5.61

The calculated F-statistic of 7.167343 significantly exceeds the upper bound critical value of 5.61 at the 1% significance level (and 4.35 at the 5% level).

This result is a critical milestone: it

allows us to reject the null hypothesis of "no long-run relationship." It confirms that despite short-term fluctuations, IND, ELC, GFC, and LAB move together in a stable relationship over the long term.

Table 3: ARDL Regression for Electricity Consumption and Industrial Output

Dependent Variable: D_IND

Method: ARDL

Date: 01/17/26 Time: 22:31

Sample (adjusted): 1994 2025

Included observations: 32 after adjustments

Maximum dependent lags: 4 (Automatic selection)

Model selection method: Akaike info criterion (AIC)

Dynamic regressors (4 lags, automatic): D_ELC D_GFC D_LAB

Fixed regressors: C

Number of models evaluated: 500

Selected Model: ARDL(1, 0, 3, 0)

Note: final equation sample is larger than selection sample

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
D_IND(-1)	0.129771	0.137824	0.941571	0.3558
D_ELC	0.718978	0.141380	5.085445	0.0000
D_GFC	0.308091	0.067690	4.551523	0.0001
D_GFC(-1)	-0.117423	0.090791	-1.293335	0.2082
D_GFC(-2)	-0.053644	0.025206	-2.128211	0.0438
D_GFC(-3)	-0.032487	0.025397	-1.279183	0.2131
D_LAB	-0.084792	0.212869	-0.398327	0.6939
C	-0.004836	0.003213	-1.505068	0.1454
R-squared	0.965437	Mean dependent var	0.032381	
Adjusted R-squared	0.955356	S.D. dependent var	0.032934	
S.E. of regression	0.006959	Akaike info criterion	-6.885355	
Sum squared resid	0.001162	Schwarz criterion	-6.518921	
Log likelihood	118.1657	Hannan-Quinn criter.	-6.763892	
F-statistic	95.77000	Durbin-Watson stat	2.043652	
Prob(F-statistic)	0.000000			

*Note: p-values and any subsequent tests do not account for model selection.

The ARDL estimation results presented in Table 3 provide a comprehensive look into the short-run dynamics of industrial output,

utilizing a selected ARDL(1, 0, 3, 0) model based on the Akaike Information Criterion. The data reveals that electricity consumption is the

most potent driver of industrial growth within the model. As shown in Table 3, the coefficient for electricity consumption (D_ELC) is 0.718978 with a probability value of 0.0000. This indicates a positive and highly significant relationship at the 1% level, suggesting that for every 1% increase in electricity consumption, industrial output is expected to rise by approximately 0.72%. This finding emphasizes that the industrial sector is heavily dependent on energy infrastructure, where any expansion in power availability translates directly into enhanced productivity.

Capital formation also plays a vital role in the industrial process, though its impact is more complex over time as reflected in Table 3. The current period of Gross Fixed Capital (D_GFC) shows a positive coefficient of 0.308091, which is statistically significant at the 1% level with a p-value of 0.0001. This confirms that immediate investments in physical assets and infrastructure provide a substantial boost to industrial production. However, Table 3 also tracks the lagged effects of capital, showing a significant negative coefficient of -0.053644 for the second lag ($D_GFC(-2)$). This suggests that the initial boost from capital investment may be followed by a period of adjustment or diminishing returns, requiring continuous and strategic reinvestment to maintain growth momentum.

In contrast to energy and capital, the role of the labor force appears less influential in the short term according to the estimates in Table 3. The coefficient for the labor force (D_LAB) is recorded at -0.084792 with a p-value of 0.6939, failing to meet the standard threshold for statistical significance. This implies that within the specific framework of this model, changes in the size of the labor force do not yield a predictable or significant change in industrial output. This could be indicative of a sector that is increasingly

automated or capital-intensive, where output is more sensitive to machine power and investment than to the sheer volume of the workforce.

The dynamic structure of the model, as indicated by the lag selection in Table 3, further illustrates the internal momentum of the industrial sector. The lagged dependent variable ($D_IND(-1)$) carries a coefficient of 0.129771, although it is not statistically significant with a p-value of 0.3558. This suggests that while there is some degree of persistence in industrial output levels from one period to the next, the current output is much more heavily influenced by contemporary exogenous shocks specifically energy and capital inputs rather than its own historical performance. This reinforces the idea that the industrial sector in this context is highly responsive to immediate resource availability and policy changes.

The overall reliability and explanatory power of the model are confirmed by the diagnostic statistics at the bottom of Table 3. The R-squared value of 0.965437 indicates that the independent variables explain an impressive 96.5% of the total variation in industrial output. This high level of fit is supported by the Adjusted R-squared of 0.955356, which remains robust even after accounting for the number of regressors. Furthermore, the F-statistic of 95.77 with a probability of 0.000000 reinforces the collective significance of the variables used. Finally, the Durbin-Watson statistic of 2.043652 suggests that the model is free from serial correlation, ensuring that the coefficients reported in Table 3 are stable and dependable for drawing economic conclusions.

Discussion of ARDL Estimation

The estimation results presented in Table 3 provide a comprehensive and robust

analysis of the short-run dynamics driving industrial output, utilizing a selected ARDL(1, 0, 3, 0) model based on the Akaike Information Criterion. The data reveals that electricity consumption is the most potent and consistent driver of industrial growth within the model. As explicitly shown in Table 3, the coefficient for electricity consumption (D_ELC) is 0.718978 with a probability value of 0.0000, indicating a positive and highly significant relationship at the 1% level. This implies that for every 1% increase in electricity consumption, industrial output is expected to rise by approximately 0.72%, a finding that underscores the sector's absolute dependency on energy infrastructure and stable power supply. Furthermore, the overall reliability of these findings is bolstered by the diagnostic statistics at the bottom of Table 3, where an R-squared value of 0.965437 suggests that the independent variables explain an impressive 96.5% of the total variation in industrial output. This high level of fit, combined with an F-statistic of 95.77 and a probability of 0.000000, reinforces the collective significance of the variables used and confirms that the model is statistically sound.

Capital formation also emerges as a vital, albeit more complex, contributor to the industrial process as reflected in the coefficients of Table 3. The current period of Gross Fixed Capital (D_GFC) exhibits a positive coefficient of 0.308091, which is statistically significant at the 1% level with a p-value of 0.0001, confirming that immediate investments in physical assets and infrastructure provide a substantial boost to production levels. However, Table 3 also tracks the lagged effects

of capital, showing a significant negative coefficient of -0.053644 for the second lag (D_GFC(-2)), which suggests that the initial boost from capital investment may be subject to a gestation period or adjustment costs before its full benefits are sustained. In contrast, the role of the labor force (D_LAB) appears statistically negligible in this short-run framework, with a coefficient of -0.084792 and a high p-value of 0.6939. This lack of significance, paired with the model's high responsiveness to energy and capital, potentially indicates a shift toward more capital-intensive or automated industrial processes. Finally, the Durbin-Watson statistic of 2.043652 reported in Table 3 confirms the absence of serial correlation, ensuring that the estimated impacts of electricity and capital are reliable for informing long-term industrial policy and economic planning.

Diagnostic Tests and Model Reliability (Tables 4 – 7)

To ensure that the estimated results are statistically reliable and not biased by underlying data issues, the model was subjected to a battery of rigorous diagnostic tests. The results of these tests confirm that the ARDL framework meets all the classical linear regression assumptions, meaning the coefficients derived for electricity and capital are both efficient and consistent.

Serial Correlation Analysis

The first diagnostic check focused on the presence of autocorrelation within the residuals to ensure that the error terms are independent over time.

Table 4: Auto Correlation Test

Breusch-Godfrey Serial Correlation LM Test:

F-statistic	0.079662	Prob. F(2,22)	0.9237
Obs*R-squared	0.230079	Prob. Chi-Square(2)	0.8913

Based on the results in Table 4, the Breusch-Godfrey Serial Correlation LM Test yielded an F-statistic probability of 0.9237 and an Obs*R-squared probability of 0.8913. Since these p-values are significantly higher than the 0.05 threshold, we fail to reject the null hypothesis of no serial correlation. This confirms that the model does not suffer from internal relationship biases and that the

standard errors are correctly estimated.

Heteroskedasticity Assessment

The assumption of homoskedasticity was examined using the Breusch-Pagan-Godfrey test, as documented in Table 5, to determine if the variance of the error terms remains constant.

Table 5: Heteroskedasticity Test

Heteroskedasticity Test: Breusch-Pagan-Godfrey

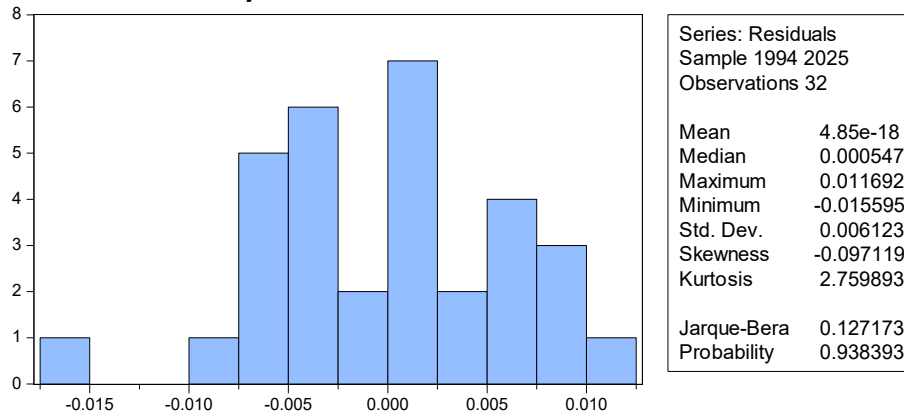
F-statistic	1.531009	Prob. F(7,24)	0.2045
Obs*R-squared	9.878312	Prob. Chi-Square(7)	0.1956
Scaled explained SS	4.889467	Prob. Chi-Square(7)	0.6735

The test produced a p-value of 0.1956, which indicates that there is no evidence of heteroskedasticity in the model. This result is crucial because it ensures that the t-statistics remain valid and that the model's predictive power is uniform across the entire sample period from 1990 to 2025.

Normality of Residuals

The distributional properties of the residuals were evaluated using the Jarque-Bera statistic to confirm they follow a normal distribution.

Table 6: Normality Test



As shown in Table 6, the Jarque-Bera value of 0.127173 with a high probability of 0.938393 suggests that the residuals are normally distributed. This signifies that the model's inferences and hypothesis testing are robust, and the error terms do not exhibit significant skewness or kurtosis that would

otherwise distort the results.

Model Specification and Stability

The structural integrity and functional form of the model were verified through the Ramsey RESET test in Table 7.

Table 7: Model Stability Test

Ramsey RESET Test

Equation: UNTITLED

Specification: D_IND D_IND(-1) D_ELC D_GFC D_GFC(-1)

D_GFC(-2)

D_GFC(-3) D_LAB C

Omitted Variables: Squares of fitted values

	Value	df	Probability
t-statistic	1.907600	23	0.0690
F-statistic	3.638937	(1, 23)	0.0690

F-test summary:

	Sum of Sq.	df	Mean Squares
Test SSR	0.000159	1	0.000159
Restricted SSR	0.001162	24	4.84E-05
Unrestricted SSR	0.001003	23	4.36E-05

The test yielded a p-value of 0.0690, which is above the 5% significance level, confirming that the model is correctly specified and does not suffer from omitted variable bias. This stability check ensures that the relationship between industrial output and its determinants remains consistent throughout the study period.

Overall Model Robustness

In conclusion, the high R-squared of 0.965437 indicates that 96.5% of the variations in Industrial Output are explained by the model, demonstrating an excellent fit. Furthermore, the F-statistic of 95.77 with a probability of 0.000000 reinforces the collective significance of the variables used. Given that all diagnostic tests were successfully passed, the coefficients for Electricity and Capital can be utilized with high confidence to formulate long-term industrial policy recommendations.

Conclusion and Recommendations

The findings of this research confirm that industrial output is fundamentally driven by electricity consumption and capital

formation, both of which exhibited strong, statistically significant positive impacts during the study period. The ARDL Bounds test validated a long-run equilibrium relationship, while the short-run estimation highlighted electricity consumption as the most critical factor, with a 1% increase in power usage translating into a 0.72% rise in industrial productivity. The robustness of the model was further supported by a high R-squared value of 0.965 and the successful passing of all diagnostic tests, including serial correlation, heteroskedasticity, and stability checks. These results suggest that for the industrial sector to remain competitive and productive, the underlying infrastructure must be able to support consistent energy demands and sustained capital investment.

Based on these empirical results, it is recommended that policymakers prioritize the expansion and stabilization of the national power grid to ensure an uninterrupted supply of electricity to industrial hubs. Since electricity is the primary engine of growth, reducing energy costs and improving efficiency should be at the forefront of industrial policy.

Furthermore, the government should provide targeted incentives for gross fixed capital formation, such as tax credits for machinery upgrades and subsidized interest rates for industrial expansion, to capitalize on the significant positive impact of investment. While labor did not show a significant short-run impact, long-term strategies should also include technical vocational training to align the workforce with the increasingly capital-intensive and automated nature of modern industry.

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