



The Productivity-Energy Nexus in Nigeria: Asymmetric Impacts of Efficiency and Factor Substitution

Fatai Asimi and Atoyebi Kehinde

Lagos State University, Faculty of Social Sciences, Ojo (Main campus), Lagos State, Nigeria

Citation: Fatai Asimi and Atoyebi Kehinde (2026) *The Productivity-Energy Nexus in Nigeria: Asymmetric Impacts of Efficiency and Factor Substitution*. *J of Eco and Soc Dynamics* 2(9), 1-19. WMJ/JESD-167

Abstract

This study investigates the dynamic relationship between energy efficiency, productivity, and factor substitution in Nigeria's manufacturing sector from 1981 to 2023. Using a post-positivist framework and secondary time-series data, we employ Stochastic Frontier Analysis (SFA) to estimate energy efficiency, a Nonlinear Autoregressive Distributed Lag (NARDL) model to assess its asymmetric impact on manufacturing output, and a Translog cost function to compute Morishima Elasticities of Substitution (MES). Results indicate an average energy efficiency score of 82.2%, highlighting significant potential for improvement. The NARDL estimates reveal that energy efficiency affects manufacturing output asymmetrically, with negative shocks exerting a disproportionately larger long-run impact than positive improvements. Furthermore, capital and energy are substitutes ($MES > 0$), while capital and labor are complements ($MES < 0$), suggesting that energy price policies could reshape the sector's input structure. The study concludes that energy efficiency is not merely an environmental or cost-saving concern but a strategic determinant of industrial productivity in Nigeria. Policy should therefore prioritize institutionalizing energy efficiency within the national industrial strategy, supported by incentives for technology adoption and skills development.

***Corresponding author:** Fatai Asimi, Lagos State University, Faculty of Social Sciences, Ojo (Main campus), Lagos State, Nigeria.

Submitted: 06.08.2026

Accepted: 12.08.2026

Published: 17.09.2026

Keywords: Energy Efficiency, Total Factor Productivity, Input Substitution, Nigerian Manufacturing, Stochastic Frontier Analysis, NARDL, Morishima Elasticity

JEL Classification: D24, L60, O14, Q43

Introduction

Energy is a fundamental input in industrial production, influencing both economic output and environmental sustainability [1]. In Nigeria, Africa's largest economy, the manufacturing sector is the second-largest consumer of refined petroleum and the largest consumer of electricity [2]. Despite this high energy intensity, the sector's contribution to Gross Domestic Product (GDP) has declined from 11.75% in 2011 to 7.61% in 2024 [2]. This paradox of rising energy use alongside stagnant performance raises critical questions about the sector's energy efficiency and its link to productivity.

Theoretical and empirical literature present a complex picture. While studies such as [3]. Subrahmanya, and Cantore et al. find that energy efficiency enhances productivity, others, such as Haider and Ganie, report a negative relationship, suggesting context-specific dynamics [4-6]. Most evidence, however, derives from developed or emerging Asian economies, creating a significant gap for sub-Saharan Africa, [7,8]. Furthermore, the potential to substitute non-energy inputs (capital, labor) for energy a key mechanism for improving efficiency remains underexplored at the aggregate level in Nigeria [9,10].

This study addresses these gaps by asking: (1) What is the extent of energy efficiency change in Nigeria's manufacturing sector? (2) How does energy efficiency affect sectoral performance, and is this relationship symmetric? (3) Do substitution possibilities exist between energy and non-energy inputs? By answering these questions, the research provides novel, policy-relevant insights into the role of energy in Nigeria's industrial development.

Theoretical Framework and Methodology

Theoretical Foundations

The study is grounded in production theory Debreu, Farrell, and the neoclassical theory of the firm [11]. Debreu introduced the coefficient of resource utilization as a measure of efficiency, while Farrell operationalized this concept by distinguishing between technical, allocative, and economic efficiency [11,12]. Technical efficiency refers to the ability of a firm to produce maximum output from a given set of inputs, while allocative efficiency refers to the ability to choose the optimal input mix given input prices. Our

study focuses primarily on technical efficiency in energy use, which we term "energy efficiency."

The production theory framework assumes that firms operate with a production possibility frontier representing the maximum output achievable for any given input combination. Firms falling below this frontier are technically inefficient. This concept is particularly relevant for energy use, as firms may use more energy than technically necessary due to various market failures, informational asymmetries, or behavioral factors.

We incorporate the Energy Efficiency Gap theory Jaffe & Stavins, to explain why firms might not adopt cost-effective energy efficiency measures [13]. This theory posits that numerous barriers including imperfect information, principal-agent problems, transaction costs, and capital market imperfections prevent firms from achieving optimal energy efficiency levels. The presence of these barriers creates an "efficiency gap" between actual and optimal energy use.

Additionally, Jovanovic's theory of firm selection provides a dynamic framework for understanding efficiency variation [14]. According to this theory, firms with lower efficiency are less likely to survive in competitive markets, suggesting that observed efficiency levels represent a selection process where more efficient firms dominate. This is particularly relevant for the Nigerian manufacturing sector, which has experienced significant structural changes and firm exits over the study period.

The interaction between energy efficiency and productivity can be understood through several mechanisms: (1) direct cost reduction through lower energy expenses, (2) improved production processes leading to higher output quality, (3) technological spillovers from energy-efficient investments, and (4) enhanced competitiveness through lower unit costs. However, these benefits may not be realized symmetrically efficiency declines may have more severe impacts than equivalent improvements due to adjustment costs, irreversible investments, and institutional rigidities.

Research Design and Philosophical Stance

The research employs a post-positivist research design,

which acknowledges that while objective reality exists, our knowledge of it is imperfect and probabilistic [15]. This stance is appropriate for quantitative analysis of economic phenomena where measurement error, model uncertainty, and structural breaks are inherent features. The post-positivist approach emphasizes hypothesis testing, statistical inference, and triangulation of evidence from multiple methods.

The study is quantitative and non-experimental, employing secondary time-series data from 1981 to 2023. This timeframe captures significant periods of oil price volatility (including the 1986 oil price collapse, the 2008 global financial crisis, and the 2014-2016 oil price crash), structural adjustment programs (the 1986 SAP that liberalized the economy), and recent power sector reforms (the 2013 privatization of PHCN). This rich historical context allows us to examine how energy efficiency dynamics respond to major structural changes.

Data Sources and Measurement

The study uses secondary time-series data from publicly available, reputable sources to ensure reliability and validity. Data sources include:

- Central Bank of Nigeria (CBN): Statistical Bulletin and Annual Reports (various years) for manufacturing output, lending rates, and macroeconomic indicators.
- National Bureau of Statistics (NBS): Annual Abstract of Statistics for energy consumption, capital stock, labor data, and sectoral output.
- World Bank: World Development Indicators for supplementary data and cross-validation
- International Energy Agency (IEA): Energy price data for crude oil and refined products.

The timeframe from 1981 to 2023 was chosen because: (1) it provides a sufficiently long time series for time-series econometric analysis (43 observations), (2) it covers periods before and after major structural reforms, and (3) it allows for meaningful historical comparisons. The choice of 1981 as the starting point is driven by data availability constraints, as consistent manufacturing data for Nigeria before this period is limited.

Table 1: Definition and Measurement of Variables

Variable Category	Variable Name	Symbol	Measurement
Dependent Variables	Manufacturing Output	MO	Total annual sales/value of output (NGN) in constant 2010 prices
	Energy Intensity	EI	Total cost of energy / Manufacturing Output (TOE per NGN million)
	Total Manufacturing Cost	C	Sum of capital, labour, and energy costs (NGN million)
Independent Variables	Capital Input	CAP	Total value of machinery and equipment (NGN million) using the perpetual inventory method
	Labour Input	LAB	Total wages paid to employees (NGN million)
	Energy Input	E	Total cost of electricity and fuel (NGN million)
	Energy Efficiency	EE	Score derived from Stochastic Frontier Analysis (0 to 1)
Price Variables	Price of Capital	P_K	User cost of capital (proxied by maximum lending rate + depreciation)
	Price of Labour	P_L	Mean wage earnings per employee (NGN per worker)
	Price of Energy	P_E	Weighted average cost per tonne of oil equivalent (TOE)

Policy Variable	Power Sector Reform Dummy	P O L - DUM	Dummy variable: 0 for years before 2013, 1 for 2013 and after
-----------------	---------------------------	-------------	---

Measurement Notes:

- Manufacturing Output: Deflated using the manufacturing GDP deflator (2010 = 100) to obtain real values.
- Capital Stock: Estimated using the perpetual inventory method: $K_t = (1-\delta)K_{t-1} + I_t$, with depreciation rate $\delta = 5\%$ and initial capital stock estimated using the Harberger method [16].
- Energy Efficiency: Derived from SFA, representing the ratio of minimum feasible energy use to actual energy use, conditional on output and other inputs.
- Price of Capital: Calculated as $P_K = r + \delta$, where r is the maximum lending rate and δ is depreciation.
- Price of Energy: Weighted average of electricity tariff and petroleum product prices.

Econometric Methodology

Unit Root and Stationarity Testing

In time series analysis, the properties of standard estimation and testing techniques depend on the assumption that the variables under consideration are stationary. Regression analysis applied to non-stationary series can yield misleading results, often referred to as "spurious regression" [17]. To address this, we conduct multiple unit root tests:

- Augmented Dickey-Fuller (ADF) Test: Tests the null hypothesis of a unit root (non-stationarity) against the alternative of stationarity.
- Phillips-Perron (PP) Test: Similar to ADF but robust to heteroskedasticity and serial correlation.
- Kwiatkowski-Phillips-Schmidt-Shin (KPSS) Test: Tests the null hypothesis of stationarity against the alternative of a unit root, providing complementary evidence.
- The testing procedure involves:
 - Testing variables in levels
 - Testing variables in first differences if non-stationary in levels
 - Determining the order of integration ($I(0)$ for stationary levels, $I(1)$ for stationary first differences)
 - Considering potential structural breaks using the Zivot-Andrews test, which allows for a single endogenous break [18].

Objective 1: Estimating Energy Efficiency (SFA)

The Stochastic Frontier Analysis (SFA) approach Aigner et al; Meeusen & van den Broeck, is superior to Data Envelopment Analysis (DEA) for our purposes because: (1) it accommodates random shocks and measurement error, (2) it provides statistical inference, and (3) it is appropriate for time-series analysis with noise [19,20]. The SFA model decomposes the error term into two components: random noise (θ_t) and inefficiency (μ_t).

We adopt an input-oriented approach, estimating a frontier energy demand function:

where:

- EI_t = Energy Intensity (energy use per unit of output)
- MO_t = Manufacturing Output
- CAP_t = Capital Input
- LAB_t = Labor Input
- $POLDUM_t$ = Dummy for the 2013 power sector reform
- θ_t = Random noise (symmetric, normally distributed)
- μ_t = Inefficiency term (non-negative, half-normal or exponential distribution)

Justification of Variables in the SFA Model:

- Manufacturing Output (MO): Included as the primary output variable determining energy requirements. Higher output generally requires more energy, though economies of scale may reduce energy intensity.
- Capital Input (CAP): Included to capture the capital-energy relationship. More capital-intensive production

may be more or less energy-efficient depending on the vintage and type of capital.

- Labor Input (**LAB**): Included to capture labor-energy substitutability. Higher labor intensity may be associated with either higher or lower energy intensity depending on production technology.
- Policy Dummy (**POLDUM**): Captures the impact of the 2013 power sector reform, which unbundled the state-owned Power Holding Company of Nigeria (PHCN) into six generating companies, ten distribution companies, and one transmission company, with private sector participation. This reform was expected to improve energy supply reliability and efficiency.

Estimation Procedure:

- Maximum Likelihood Estimation (MLE) of the frontier parameters
- Calculation of inefficiency scores using the conditional expectation of μ_t given the composite error term [21].
- Energy efficiency score: $EE_t = \exp(-\mu_t)$, ranging from 0 to 1
- Likelihood Ratio Test for the presence of inefficiency: $LR = -2[LLF_{restricted} - LLF_{unrestricted}]$

Objective 2: Assessing Asymmetric Impact on Productivity (NARDL)

To capture asymmetric effects, we employ a Nonlinear Autoregressive Distributed Lag (NARDL) model [22]. The NARDL model was chosen because: (1) it allows for the examination of distinct positive and negative effects of energy efficiency on manufacturing output, (2) it accommodates variables with different orders of integration (I(0) and I(1)), (3) it provides both short-run and long-run asymmetry tests, and (4) it is suitable for small samples [23].

The NARDL approach involves three steps:

Step 1: Partial Sum Decomposition

The energy efficiency variable is decomposed into positive and negative partial sums:

$$EE_t = EE_0 + EE_t^+ + EE_t^-$$

where:

$$EE_t^+ = \sum_{i=1}^t \max(\Delta, EE_i 0)$$

$$EE_t^- = \sum_{i=1}^t \min(\Delta, EE_i 0)$$

This decomposition separates cumulative increases in efficiency from cumulative decreases, allowing them to have potentially different coefficients.

Step 2: Model Specification

The NARDL model is specified as:

$$\Delta MO_t = \gamma + \sum_{i=1}^p \alpha_i \Delta MO_{t-i} + \sum_{i=0}^q \beta_i^+ \Delta EE_t^+ + \sum_{i=0}^q \beta_i^- \Delta EE_t^- + \sum_{i=0}^r \delta_i \Delta X_{t-i} + \varphi ECM_{t-1} + \varepsilon_t$$

where:

- MO_t = Manufacturing Output (log)
- EE_t^+ and EE_t^- = Partial sum decompositions of energy efficiency
- X_t = Vector of control variables (CAP, LAB, EI, POLDUM)
- ECM_{t-1} = Error Correction Term
- p, q, r = Lag lengths determined by Akaike Information Criterion (AIC) or Schwarz Bayesian Criterion (SBC)

- γ = Constant term
- φ = Speed of adjustment coefficient (negative and significant for cointegration)

Step 3: Testing for Asymmetry and Cointegration

- Bounds Test for Cointegration: Tests the null hypothesis of no cointegration ($\theta^+ = \theta^- = \rho = 0$) against the alternative of cointegration. The F-statistic is compared to critical values provided by Pesaran et al. with the I(0) bound representing stationarity and I(1) bound representing integration of order one [23].
- Long-run Asymmetry Test: Tests $H_0: \theta^+ = \theta^-$ using a Wald test or F-test. Rejection indicates that positive and negative efficiency changes have different long-run impacts.
- Short-run Asymmetry Test: Tests $H_0: \sum_{i=0}^q \beta_i^+ = \sum_{i=0}^q \beta_i^-$ using a Wald test. Rejection indicates asymmetric short-run dynamics.
- The long-run coefficients for positive and negative changes are calculated as:

$$\theta^+ = -\frac{\sum_{i=0}^q \beta_i^+}{\varphi}$$

$$\theta^- = -\frac{\sum_{i=0}^q \beta_i^-}{\varphi}$$

Interpretation of Asymmetric Effects:

- If $\theta^+ > 0$ and significant, improvements in energy efficiency increase manufacturing output.
- If $\theta^- < 0$ and significant, declines in energy efficiency decrease manufacturing output.
- If $|\theta^-| > |\theta^+|$, the impact of efficiency declines is greater than that of equivalent improvements (negative asymmetry), indicating that the sector is more vulnerable to efficiency losses than it benefits from gains.

The manufacturing sector's input substitution possibilities are crucial for understanding how changes in relative input prices affect production decisions. The Translog cost function Christensen et al., provides a flexible second-order approximation to any arbitrary cost function, allowing for non-constant elasticities of substitution [24].

Justification for the Translog Approach:

Compared to more restrictive functional forms (Cobb-Douglas or CES), the Translog form: (1) does not impose constant elasticities of substitution, (2) allows for non-homotheticity, (3) is consistent with multiple inputs, and (4) provides second-order flexibility at the point of approximation.

Model Specification:

We estimate a Translog cost function for three inputs (capital, labor, energy):

$$\ln C = \alpha_0 + \sum_i \alpha_i \ln P_i + \frac{1}{2} \sum_i \sum_j \alpha_{ij} \ln P_i \ln P_j + \alpha_Q \ln Q + \frac{1}{2} \alpha_{QQ} (\ln Q)^2$$

$$+ \sum_i \alpha_{iQ} \ln P_i \ln Q + \alpha_T T + \frac{1}{2} \alpha_{TT} T^2 + \sum_i \alpha_{iT} \ln P_i T + \alpha_{QT} \ln Q T + \varepsilon$$

where:

- C = Total cost
- P_i = Price of input i (K, L, E)
- Q = Output
- T = Time trend (capturing technological change)
- ε = Error term

Symmetry and Homogeneity Restrictions:

To ensure consistency with economic theory, we impose:

- Symmetry: $\alpha_{ij} = \alpha_{ji}$
- Linear homogeneity in prices: $\sum_i \alpha_i = 1$, $\sum_i \alpha_{ij} = 0$, $\sum_i \alpha_{iQ} = 0$, $\sum_i \alpha_{iT} = 0$

Cost Share Equations:

Using Shephard's Lemma, the cost share of input i is:

$$S_i = \frac{\partial \ln C}{\partial \ln P_i} = \alpha_i + \sum_j \alpha_{ij} \ln P_j + \alpha_{iQ} \ln Q + \alpha_{iT} \ln T$$

Estimation Procedure:

We estimate the cost function and share equations jointly using Iterated Seemingly Unrelated Regression (iSUR):

- The system of equations is seemingly unrelated because the error terms across equations are correlated.
- Iteration ensures convergence and efficiency.
- One share equation is dropped to avoid singularity, with parameters recovered using homogeneity restrictions.

Computation of Morishima Elasticities of Substitution (MES):

Following Blackorby and Russell, the MES between inputs i and j is [25]:

$$MES_{ij} = \frac{d \ln(X_i/X_j)}{d \ln P_j} = \epsilon_{ij} - \epsilon_{jj}$$

where:

- ϵ_{ij} = Cross-price elasticity of demand for input i with respect to price j
- ϵ_{jj} = Own-price elasticity of demand for input j

For the Translog cost function:

$$\epsilon_{ij} = \frac{\alpha_{ij} + S_i S_j}{S_i}$$

$$\epsilon_{jj} = \frac{\alpha_{jj} + S_j^2 - S_j}{S_j}$$

Interpretation of MES:

- $MES_{ij} > 0$: Inputs i and j are substitutes—an increase in the price of input j leads to an increase in the ratio of input i to input j .
- $MES_{ij} < 0$: Inputs i and j are complements—an increase in the price of input j leads to a decrease in the ratio of input i to input j .
- $MES_{ii} = 0$: Inputs are independent.
- The MES is preferred to the Allen-Uzawa Elasticity of Substitution (AES) because: (1) it is asymmetric, distinguishing between changes in the price of i versus j , (2) it is more interpretable when multiple inputs are present, and (3) it is derived from the Allen-Uzawa elasticity but provides more information.

Results and Discussion

Descriptive Statistics and Stationarity Tests

Table 2: Descriptive Statistics (1981-2023)

Variable	Mean	Median	Std. Dev.	Min	Max
MO (NGN billion)	1847	1562	1092	452.8	4217
EI (TOE/NGN million)	3.42	3.18	1.24	1.87	6.53

CAP (NGN billion)	2135	1876	1325	523.4	5124
LAB (NGN billion)	1246	1098	724	324.7	2867
EE (SFA score)	0.822	0.841	0.15	0.498	0.96
P_K (%)	18.72	17.5	5.84	11.25	32.1
P_L (NGN '000)	2846	2512	1543	876.3	5674
P_E (NGN/TOE)	124.6	118.4	58.4	52.14	257

Interpretation: The descriptive statistics reveal substantial variation across all variables over the study period. Manufacturing output shows steady growth from 452.8 billion NGN in 1981 to 4,216.7 billion NGN in 2023, representing a 9.3-fold increase. However, energy intensity has declined from 6.53 TOE per million NGN in the early 1980s to 1.87 in recent years, indicating improved energy efficiency over time. The energy efficiency score from SFA ranges from 0.498 (minimum efficiency) to 0.962 (near maximum efficiency), with a mean of 0.822, suggesting that the sector operates at approximately 82.2% of potential efficiency. The wide range of P_K (11.25% to 32.14%) reflects the volatile interest rate environment in Nigeria, driven by monetary policy responses to inflation and exchange rate pressures.

Table 3: Unit Root Test Results

Variable	ADF (Level)	ADF (1st Diff)	PP (Level)	PP (1st Diff)	KPSS (Level)	KPSS (1st Diff)	Order
ln(MO)	-2	-4.872***	-2	-4.924***	0.742**	0.1	I(1)
ln(EI)	-2.876*	-6.134***	-2.765*	-6.092***	0.1	-	I(0)/I(1)
ln(CAP)	-2	-5.213***	-1.4	-5.087***	0.823***	0.1	I(1)
ln(LAB)	-2	-4.987***	-2.1	-4.876***	0.654**	0.1	I(1)
EE	-3.012**	-	-2.987**	-	0.1	-	I(0)
ln(P_K)	-2	-5.432***	-2.1	-5.321***	0.678**	0.1	I(1)
ln(P_L)	-2	-5.087***	-1.8	-5.012***	0.721**	0.1	I(1)
ln(P_E)	-2.654*	-	-2.543*	-	0.1	-	I(0)

*Note: ***, *, * indicate significance at 1%, 5%, and 10% levels respectively. Critical values: ADF/PP at 1% = -3.61, 5% = -2.94, 10% = -2.60; KPSS at 1% = 0.739, 5% = 0.463, 10% = 0.347.

Interpretation: The unit root tests reveal a mixed order of integration across variables, justifying the use of both SFA (which can handle I(0) variables) and NARDL (which accommodates both I(0) and I(1) variables). Manufacturing output, capital, labor, and the price of capital are I(1), requiring first differencing for stationarity. Energy intensity, energy efficiency, and the price of energy are I(0), being stationary in levels. The mixture of integration orders confirms that OLS estimation would be invalid, reinforcing the need for cointegration-based approaches. The Zivot-Andrews test (not shown) indicated a structural break in energy intensity and manufacturing output around 2013, coinciding with the power sector reform, providing justification for including the POLDUM variable.

Energy Efficiency Trends (Objective 1)

The SFA results reveal an average energy efficiency score of 0.822 (82.2%) for the period, with a standard deviation of 0.151. This indicates substantial room for improvement, consistent with the Energy Efficiency Gap theory [13]. The likelihood ratio test (LR = 7.44, p = 0.003) confirms the presence of significant technical inefficiency, rejecting the null hypothesis of no inefficiency in the model.

Table 4: Stochastic Frontier Analysis Results

Variable	Coefficient	Std. Error	z-statistic	p-value
Constant	-39.165	8.25	-4.7	0
ln_MO	2.284	0.42	5.45	0
ln_CAP	-1.213	0.28	-4.3	0
ln_LAB	2.134	0.39	5.44	0
POLDUM	-1.669	0.32	-5.3	0
σ_μ	0.716	0.08	-	-
σ_v	1.58E-08	0	-	-
λ	45400000	-	-	-
Log-likelihood	-	-	-	-
LR Test	7.44	-	-	0

Detailed Interpretation of SFA Coefficients:

Manufacturing Output (ln_MO): Coefficient = 2.284, $p = 0.000$. This positive and significant coefficient indicates that a 1% increase in manufacturing output is associated with a 2.28% increase in energy intensity, ceteris paribus. This finding suggests that the manufacturing sector exhibits increasing energy intensity at higher output levels, which could be driven by: (1) composition effects the sector may shift toward more energy-intensive sub-sectors during periods of output expansion, (2) capacity utilization effects fixed energy costs are spread over more output, potentially increasing the energy-output ratio if variable costs increase disproportionately, or (3) technological constraints existing production technologies may have limited scope for energy savings at higher output levels. This result contrasts with findings from developed countries where output growth is often associated with declining energy intensity, suggesting that Nigeria's manufacturing growth has not been accompanied by significant structural transformation toward less energy-intensive activities.

Capital Input (ln_CAP): Coefficient = -1.213, $p = 0.000$. This negative and significant coefficient indicates that a 1% increase in capital stock reduces energy intensity by approximately 1.21%. This is a highly policy-relevant finding, suggesting that capital deepening in the manufacturing sector has been associated with improved energy efficiency. The mechanism likely involves: (1) replacement of old, inefficient machinery with modern, energy-efficient equipment, (2) adoption of automated production processes that optimize energy use, (3) installation of energy management systems, and (4) investments in combined heat and power systems. This result aligns with the "factor substitution" hypothesis capital and energy are substitutes, meaning that increasing capital intensity can reduce energy use per unit of output. The magnitude of the effect (elasticity > 1) suggests that capital investments have been particularly effective at reducing energy intensity, possibly due to the poor initial condition of capital stock and the "low-hanging fruit" nature of efficiency improvements.

Labor Input (ln_LAB): Coefficient = 2.134, $p = 0.000$. This positive and significant coefficient indicates that a 1% increase in labor input is associated with a 2.13% increase in energy intensity. This finding suggests that labor-intensive production processes in Nigeria's manufacturing sector are relatively energy-inefficient. Several explanations are plausible: (1) labor-intensive firms may lack capital for energy-efficient technologies, (2) manual production processes may waste energy through lack of precise control, (3) the composition of labor-intensive sub-sectors (e.g., textiles, food processing) may be inherently more energy-intensive than capital-intensive sectors, and (4) labor-intensive firms may face different incentives regarding energy conservation. This result has important policy implications, as it suggests that promoting labor-intensive growth may inadvertently increase energy intensity unless accompanied by efficiency measures.

Policy Dummy (POLDUM): Coefficient = -1.669, $p = 0.000$. This negative and significant coefficient indicates that the 2013 power sector reform was associated with a 1.67% reduction in energy intensity, *ceteris paribus*. This represents a substantial policy impact and confirms the importance of institutional and regulatory frameworks for energy efficiency. The power sector reform in Nigeria involved the unbundling and privatization of PHCN, creating six generating companies, ten distribution companies, and one transmission company. The reform aimed to: (1) improve generation capacity through private investment, (2) enhance distribution efficiency, (3) reduce system losses, and (4) improve billing and collection. The finding that energy intensity declined significantly after 2013 suggests that these reforms had tangible benefits for manufacturing energy efficiency. However, the coefficient should be interpreted cautiously, as other factors (e.g., economic conditions, infrastructure investments) may have also contributed to the decline.

Time Trend of Energy Efficiency:

The energy efficiency scores estimated from SFA show an upward trend over the study period:

- 1981-1990: Average EE = 0.724 (72.4%), with significant volatility due to oil price shocks and economic instability.
- 1991-2000: Average EE = 0.789 (78.9%), reflecting gradual improvement but with a dip during the 1998 economic crisis.
- 2001-2010: Average EE = 0.843 (84.3%), showing steady improvement driven by increased private sector investment and the implementation of the National Energy Policy.
- 2011-2023: Average EE = 0.876 (87.6%), with the post-2013 reform period showing the highest efficiency levels.

This upward trend, while encouraging, still indicates that the sector operates at only 82.2% of potential efficiency on average, implying that there remains significant scope for improvement without substantial new investment (the "low-hanging fruit" of energy efficiency).

Comparison with Other Studies:

Our average energy efficiency estimate of 82.2% is comparable to: (1) 81.5% for Indian manufacturing Haider & Ganie, (2) 83.1% for Chinese manufacturing Zha & Ding, but lower than (3) 87.5% for South Korean manufacturing Park & Kim and (4) 89.3% for US manufacturing [3,6,10,26]. The lower efficiency relative to advanced economies reflects Nigeria's developmental stage and infrastructure challenges.

Asymmetric Impact on Manufacturing Output (Objective 2)

The NARDL model (optimal lag structure: 1,1,1,1,1 based on AIC) confirms a long-run cointegrating relationship. The results demonstrate a significant but **asymmetric** impact of energy efficiency on manufacturing output.

Table 5: NARDL Bounds Test for Cointegration

Test Statistic	Value	1% Critical Value	5% Critical Value	10% Critical Value
F-statistic	9.0357	5.15 (I0)	3.79 (I0)	3.17 (I0)
		6.36 (I1)	4.85 (I1)	4.14 (I1)

Interpretation: The F-statistic of 9.0357 exceeds the upper-bound critical value at the 1% level (6.36), confirming the presence of a long-run cointegrating relationship among the variables. This means that manufacturing output, energy efficiency, capital, labor, energy intensity, and the policy dummy move together in the long run, with deviations from equilibrium being corrected over time. The evidence of cointegration justifies the estimation of long-run coefficients and error correction terms

Table 6: NARDL Error Correction Model Results

Variable	Coefficient	Std. Error	t-statistic	p-value
----------	-------------	------------	-------------	---------

ECM(-1)	-0.194	0.042	-4.619	0
$\Delta MO(-1)$	0.356	0.098	3.633	0.001
$\Delta EE+$	0.284	0.084	3.381	0.002
$\Delta EE-$	-0.517	0.142	-3.641	0.001
ΔCAP	0.412	0.104	3.962	0
ΔLAB	-0.298	0.087	-3.425	0.001
ΔEI	-0.124	0.045	-2.756	0.008
$\Delta POLDUM$	0.087	0.054	1.611	0.114
Constant	0.043	0.018	2.389	0.021

Interpretation of Error Correction Term:

The error correction term (ECM(-1)) is -0.194 and significant at the 1% level ($p = 0.000$). This implies that approximately 19.4% of any deviation from long-run equilibrium is corrected within one year, indicating a relatively slow adjustment process. The negative and significant coefficient confirms cointegration and validates the long-run interpretation of the model. The speed of adjustment suggests that it would take approximately 5 years ($1/0.194$) for a shock to fully dissipate, which is plausible given the investment cycle in manufacturing. The negative coefficient on ECM also implies that when manufacturing output is above its long-run equilibrium (positive deviation), the ECM term is positive and negative adjustment occurs to restore equilibrium. Conversely, when output is below equilibrium, adjustment occurs upward.

Table 7: NARDL Model - Long-run Coefficients

Variable	Coefficient	Std. Error	t-statistic	p-value
EE+	0.9346	0.3662	2.552	0.012
EE-	2.2447	0.9321	2.408	0.018
CAP	0.9839	0.1845	5.333	0
LAB	-0.9627	0.2743	-3.51	0.001
EI	-0.2609	0.0782	-3.336	0.001
POLDUM	0.6376	0.5821	1.095	0.278
Trend	0.0315	0.0201	1.567	0.124

Detailed Interpretation of Long-run Coefficients:

Positive Energy Efficiency Changes (EE+): Coefficient = 0.9346, $p = 0.012$. This indicates that a 1% improvement in energy efficiency is associated with a 0.93% increase in manufacturing output in the long run, *ceteris paribus*. This effect operates through multiple channels: (1) direct cost reduction—lower energy costs improve profitability and allow for reinvestment, (2) improved production processes—energy efficiency measures often involve upgrading technology and optimizing processes, which can increase output quality and quantity, (3) enhanced competitiveness—lower unit costs allow firms to expand market share, and (4) reduced downtime—more reliable energy supply through efficiency measures reduces production interruptions. The positive effect confirms the "productivity dividend" of energy efficiency identified in the literature [3,4].

Negative Energy Efficiency Changes (EE-): Coefficient = 2.2447, $p = 0.018$. This indicates that a 1% decline in energy efficiency is associated with a 2.24% decrease in manufacturing output. The magnitude is approximately 2.4 times larger than the positive effect of an equivalent efficiency improvement. This asymmetry is the central finding of our analysis and has profound implications. The disproportionate impact of efficiency declines suggests that the manufacturing sector is asymmetrically vulnerable to efficiency losses. This may be due to: (1) irreversibility of investments—once firms have invested in energy-efficient technology, efficiency losses may lead to stranded assets or underutilized capacity, (2) adjustment costs—restoring efficiency after a decline

may require substantial investment, (3) confidence effects—efficiency declines may signal broader economic problems, affecting investment and output, and (4) multi-dimensional effects—efficiency declines may affect not just energy use but also product quality, employee morale, and supply chain relationships.

Symmetry Tests:

- Long-run symmetry: F-statistic = 11.6125, p-value = 0.002 (Reject H₀ of symmetry)
- Short-run symmetry: F-statistic = 5.9976, p-value = 0.007 (Reject H₀ of symmetry)
- Joint symmetry: F-statistic = 4.8723, p-value = 0.014 (Reject H₀ of symmetry)

These test results confirm that the impact of energy efficiency on manufacturing output is significantly asymmetric in both the short and long run.

Capital Input (CAP): Coefficient = 0.9839, p = 0.000. A 1% increase in capital stock is associated with a 0.98% increase in manufacturing output, highlighting the importance of capital accumulation for manufacturing growth. The coefficient is close to unity, suggesting constant returns to capital in the long run. This finding underscores the need for policies that promote investment in manufacturing capital.

Labor Input (LAB): Coefficient = -0.9627, p = 0.001. The negative coefficient suggests that labor input is inversely related to manufacturing output in the long run, after controlling for other factors. This counterintuitive finding may reflect: (1) labor redundancies and low productivity in Nigeria's manufacturing sector, (2) composition effects where labor-intensive sectors have underperformed, or (3) the possibility that labor is measured as total wages, which may have increased due to wage inflation rather than productivity gains. Alternatively, it could indicate that the sector has experienced "jobless growth"—output growth driven by capital and efficiency rather than labor. This finding aligns with the broader literature on structural transformation in Sub-Saharan Africa, where manufacturing employment has not kept pace with output growth.

Energy Intensity (EI): Coefficient = -0.2609, p = 0.001. A 1% increase in energy intensity (more energy per unit of output) is associated with a 0.26% decrease in manufacturing output, consistent with the notion

that higher energy intensity reflects inefficiency and reduces competitiveness.

Policy Dummy (POLDUM): Coefficient = 0.6376, p = 0.278. While positive, the coefficient is not statistically significant at conventional levels. This suggests that while the 2013 reform may have had beneficial effects (as shown in the SFA results), its impact on manufacturing output is not robustly identified in the NARDL model. This may reflect: (1) the relatively short post-reform period (2013-2023), (2) the gradual nature of reform impacts, or (3) confounding effects of other factors during the period.

Trend: Coefficient = 0.0315, p = 0.124. The positive but insignificant trend suggests a weak upward drift in manufacturing output over time, consistent with Nigeria's slow industrial growth.

Short-Run Dynamics:

The short-run coefficients (from the error correction model) reveal that immediate responses to efficiency changes are smaller in magnitude than long-run effects:

- Positive efficiency shock ($\Delta EE+$): 0.284 (significant at 1%)
- Negative efficiency shock ($\Delta EE-$): -0.517 (significant at 1%)

The asymmetry is also present in the short run, with the magnitude of negative shocks (0.517) exceeding that of positive shocks (0.284) by a factor of 1.82. The smaller short-run coefficients (compared to long-run coefficients) reflect adjustment costs and gradual accumulation of effects over time.

Dynamic Multiplier Analysis:

The NARDL framework allows computation of dynamic multipliers showing the cumulative impact of efficiency changes over time. The multipliers indicate:

- A positive efficiency shock reaches its full effect after approximately 3-4 years.
- A negative efficiency shock has an immediate impact that intensifies over time, reflecting cascading effects through supply chains and confidence channels.
- The asymmetric gap between positive and negative shocks widens over time, with the cumulative effect of negative shocks being 2-3 times larger than positive shocks after 5 years. This dynamic pattern has important implications: policymakers should prioritize preventing efficiency declines over

pursuing efficiency improvements, as prevention appears to be more effective than cure.

Robustness Checks:

To ensure the reliability of the NARDL results, we conducted several robustness checks:

- Alternative lag structures: The results remained robust to variations in lag length.
- Alternative estimation methods: Dynamic OLS and Fully Modified OLS yielded similar asymmetric patterns.
- Sub-sample analysis: Excluding the post-2013 reform period did not materially change the results.
- Alternative dependent variables: Using value added instead of output as the dependent variable produced consistent findings.
- Non-parametric analysis: Local polynomial regression confirmed the nonlinear, asymmetric relationship.

Input Substitution Possibilities (Objective 3)

The Translog cost function estimates fit well, with an R^2 of 0.9934 for the cost function and the share equations. The system estimation satisfied all regularity conditions at the sample mean, including monotonicity (positive predicted shares) and concavity (negative semidefinite Hessian). The model also satisfied symmetry and homogeneity restrictions, supporting the theoretical validity of the estimates.

Table 8: Translog Cost Function Parameter Estimates

Parameter	Estimate	Std. Error	p-value
α_0	1.876	0.432	0
α_K	0.342	0.052	0
α_L	0.387	0.058	0
α_E	0.271	0.047	0
α_{KK}	0.124	0.031	0
α_{LL}	0.098	0.027	0
α_{EE}	0.087	0.024	0
α_{KL}	-0.045	0.018	0.012
α_{KE}	-0.079	0.021	0
α_{LE}	-0.008	0.015	0.587
α_Q	0.876	0.098	0
α_{QQ}	0.045	0.012	0
α_{KQ}	0.032	0.009	0
α_{LQ}	-0.018	0.008	0.024
α_{EQ}	-0.014	0.007	0.041
α_T	0.023	0.011	0.038
α_{TT}	0.001	0.0004	0.012
α_{KT}	0.005	0.002	0.016
α_{LT}	-0.003	0.002	0.098
α_{ET}	-0.002	0.001	0.112

Interpretation of Parameter Estimates:

The positive own-price parameters (α_{KK} , α_{LL} , α_{EE}) indicate that cost shares increase with their own prices, a necessary condition for the cost function to be well-behaved. The negative cross-price parameters between capital and energy ($\alpha_{KE} = -0.079$) and capital and labor ($\alpha_{KL} = -0.045$) suggest substitution possibilities between these inputs. The positive coefficient on output ($\alpha_Q = 0.876$) indicates economies of scale, as a 1% increase in output leads to less than a 1% increase in cost. This suggests that the manufacturing sector exhibits

increasing returns to scale, consistent with the "big push" theories of industrialization.

Table 9: Morishima Elasticities of Substitution - Summary Statistics

Elasticity	Mean	Std. Dev.	Min	Max	Interpretation
MES_KE	3.659	0.862	1.948	4.496	Substitutes
MES_EK	3.241	0.734	1.876	4.023	Substitutes
MES_EL	2.318	0.275	1.927	2.714	Substitutes
MES_LE	2.087	0.298	1.654	2.498	Substitutes
MES_KL	-1.937	0.432	-2.484	-1.165	Complements
MES_LK	-1.683	0.389	-2.198	-0.987	Complements

Detailed Interpretation of Morishima Elasticities:

Capital and Energy Substitution (MES_KE = 3.659):

The positive MES for capital-energy (3.659) indicates that a 1% increase in the price of energy would increase the capital-energy ratio by approximately 3.66%, holding output and other input prices constant. This is a substantial substitution effect, suggesting that firms in Nigeria's manufacturing sector have significant flexibility to adjust their input mix in response to energy price changes. Specifically, when energy prices rise, firms can substitute capital for energy by: (1) investing in energy-efficient equipment, (2) replacing old, inefficient machinery with modern, energy-saving capital, (3) installing energy management systems, and (4) adopting new production technologies that are less energy-intensive.

The symmetric MES_EK (3.241) indicates that a 1% increase in the price of capital would increase the energy-capital ratio by approximately 3.24%, meaning firms would substitute energy for capital when capital becomes more expensive. The asymmetry between MES_KE and MES_EK (3.659 vs. 3.241) reflects the fact that the two elasticities are generally not equal in the Morishima framework.

Policy Implications of Capital-Energy Substitution:

The strong capital-energy substitutability has profound policy implications:

- **Energy Price Policies:** Increases in energy prices (e.g., through removal of subsidies or carbon pricing) will likely accelerate capital deepening and energy efficiency improvements.
- **Investment Incentives:** Policies that reduce the cost of capital (e.g., tax incentives for investment, lower interest rates, or investment tax credits) would encourage energy efficiency by making it cheaper to substitute capital for energy.
- **Environmental Regulation:** Stricter environmental standards would incentivize capital investment in cleaner technologies, reducing energy intensity.
- **Infrastructure Development:** Improved electricity infrastructure would reduce the need for self-generation, altering the capital-energy relationship.

Energy and Labor Substitution (MES_EL = 2.318):

The positive MES for energy-labor (2.318) indicates that a 1% increase in the price of energy would increase the energy-labor ratio by approximately 2.32%, suggesting that firms substitute labor for energy when energy prices rise. This could occur through: (1) labor-intensive production processes that require less energy, (2) manual operations replacing automated ones, or (3) shifts to production methods with lower energy intensity. The relatively smaller magnitude (compared to capital-energy substitution) suggests that labor-energy substitution is less flexible than capital-energy substitution. This may reflect: (1) the nature of production processes where some energy use is required regardless of labor input, (2) the skill composition of the labor force (labor and energy may be complements in skilled tasks), or (3) technology constraints.

The symmetric MES_LE (2.087) indicates that a 1% increase in the price of labor would increase the energy-

labor ratio by approximately 2.09%, suggesting firms substitute energy for labor when wages rise.

Policy Implications of Energy-Labor Substitution:

- **Employment Effects:** Rising energy prices could potentially increase employment (as firms substitute labor for energy), though the effect is modest.
- **Training and Skills:** The substitution suggests that energy price policies should be accompanied by training programs to develop the skills needed for labor-intensive, energy-efficient production.
- **Labor Market Policies:** Labor market rigidities could impede substitution, reducing the effectiveness of energy policies.

Capital and Labor Complementarity (MES_{KL} = -1.937):

The negative MES for capital-labor (-1.937) indicates that capital and labor are complements in Nigeria's manufacturing sector. This means that a 1% increase in the price of labor would decrease the capital-labor ratio by approximately 1.94%, or equivalently, an increase in capital investment is associated with increased demand for labor. This complementarity suggests that:

- **Capital Deepening Creates Jobs:** Rather than displacing workers, capital investment creates demand for complementary labor, particularly skilled workers who operate and maintain the capital equipment.
- **Skill-Biased Technological Change:** The complementarity may reflect skill-biased technological change, where new capital requires more skilled workers, not fewer.
- **Production Organization:** Capital-labor complementarity indicates that production processes in Nigeria are organized such that capital and labor work together, rather than one replacing the other.
- The symmetric MES_{LK} (-1.683) indicates that a 1% increase in the price of capital would decrease the labor-capital ratio by approximately 1.68%.

Policy Implications of Capital-Labor Complementarity:

- **Training and Skills Development:** Policies to promote capital investment should be accompanied by training and skills development to ensure a supply of complementary labor.
- **Employment Effects:** The complementarity

suggests that capital investment is not necessarily employment-reducing, countering fears that automation will lead to mass unemployment.

- **Education Policy:** Investments in education and technical skills are essential for reaping the benefits of capital investment.
- **Industrial Policy:** Complementary relationships suggest that industrial policies should consider the interdependencies between capital, labor, and energy.

Comparison with Other Studies:

Our MES estimates are generally consistent with international evidence:

- Capital-energy substitution (MES = 3.66) is higher than in China (MES = 1.82 from Zha & Ding, but comparable to India (MES = 3.12) [6,10].
- Energy-labor substitution (MES = 2.32) is similar to the US (MES = 2.15 from [3].
- Capital-labor complementarity (MES = -1.94) is more pronounced than in China (MES = -0.87) but similar to other developing countries.
- The relatively high elasticities in Nigeria may reflect the sector's "dualistic" structure, with traditional, labor-intensive firms coexisting with modern, capital-intensive firms, allowing for substantial substitution along the margin.

Synthesis and Discussion

Integration of Findings

The three objectives of this study provide complementary insights into the energy-productivity nexus in Nigeria's manufacturing sector:

From SFA (Objective 1): The sector operates at 82.2% energy efficiency, with capital investment and policy reforms improving efficiency, while labor input is associated with higher energy intensity. This establishes the "efficiency gap" and identifies its key determinants. From NARDL (Objective 2): Energy efficiency asymmetrically affects manufacturing output, with efficiency declines having disproportionately larger negative impacts than the positive impacts of equivalent improvements. This reveals the "risk asymmetry" in the sector's energy-productivity relationship.

From Translog/MES (Objective 3): Input substitution possibilities exist but are asymmetric: capital and energy are strong substitutes, energy and labor are modest

substitutes, and capital and labor are complements. This identifies the mechanisms through which efficiency improvements and declines operate.

Together, these findings paint a comprehensive picture of the energy-productivity nexus:

- **Efficiency Matters:** The sector has room for improvement, and improvements in efficiency boost output.
- **Declines are Dangerous:** Efficiency declines are more harmful than improvements are beneficial, creating a "downside risk" that policymakers should prioritize preventing.
- **Substitution Exists but is Constrained:** Firms can adjust their input mix in response to relative price changes, but the nature of substitution varies across inputs, with important implications for policy design.

Theoretical Implications

Our findings contribute to and refine several theoretical frameworks:

Production Theory (Debreu, Farrell): The empirical results demonstrate that firms in Nigeria's manufacturing sector are not all operating on the production possibility frontier, validating the concept of technical inefficiency. The variation in efficiency across firms (as captured by the SFA score distribution) supports the notion that there is a distribution of efficiency levels, not a single level [11,12].

Energy Efficiency Gap Theory Jaffe & Stavins: The existence of significant inefficiency (average EE = 82.2%) despite the positive output effects of efficiency improvement (EE+ coefficient = 0.93) provides strong evidence for the energy efficiency gap [13]. Firms are not adopting cost-effective energy efficiency measures, likely due to market failures, informational asymmetries, and institutional barriers. The reduction in energy intensity following the 2013 power sector reform suggests that institutional factors are important in closing this gap.

Jovanovic's Theory of Firm Selection: The asymmetry between positive and negative efficiency shocks suggests that efficiency declines lead to firm exit, while efficiency improvements do not necessarily lead to entry [14]. This is consistent with Jovanovic's

selection model, where low-efficiency firms are more likely to exit than high-efficiency firms are to enter. The larger negative impact of efficiency declines may reflect the "destructive" nature of selection.

Neoclassical Theory of the Firm: The substitution patterns (capital-energy substitutes, capital-labor complements) are broadly consistent with neoclassical production theory, though they refine our understanding of the specific relationships in the Nigerian context. The complementarity between capital and labor suggests that the traditional narrative of technology replacing labor may not be applicable to Nigeria, where capital and labor work together rather than in opposition.

Methodological Contributions

This study advances methodological approaches to analyzing the energy-productivity nexus:

- **Integration of SFA and NARDL:** By combining frontier analysis with asymmetric cointegration, we capture both the level of efficiency and its nonlinear effects on output. This is a methodological innovation that could be applied to other contexts.
- **Use of Morishima Elasticities:** The use of MES rather than Allen-Uzawa elasticities provides a more accurate and policy-relevant measure of input substitution, as MES is asymmetric and directly relates to input proportions.
- **Dynamics of Asymmetry:** The NARDL approach allows us to distinguish between short-run and long-run asymmetry, providing a more complete understanding of how efficiency shocks propagate through the economy.
- **Contextualized Application:** The application of these sophisticated methods to a Sub-Saharan African context addresses a significant gap in the literature, where most studies focus on developed or emerging Asian economies.

Policy Implications

The findings have several important policy implications:

Institutionalizing Energy Efficiency in Industrial Strategy:

The finding that energy efficiency has a significant positive impact on manufacturing output (0.93% increase per 1% efficiency improvement) suggests that energy efficiency should be treated as a strategic priority, not just an environmental concern. Nigeria's industrial

policy should explicitly integrate energy efficiency goals, with clear targets, monitoring mechanisms, and enforcement.

Preventing Efficiency Declines:

The asymmetry result that efficiency declines are 2.4 times more harmful than improvements are beneficial implies that policy should focus on preventing declines as much as promoting improvements. This suggests:

- **Risk management:** Policies to reduce vulnerability to energy price volatility, such as hedging mechanisms, strategic reserves, and price stabilization funds.
- **Infrastructure investment:** Reducing the likelihood of power outages and fuel shortages that could lead to efficiency declines.
- **Early warning systems:** Monitoring energy efficiency indicators to detect declines early and intervene before they become entrenched.

Leveraging Capital-Energy Substitution:

The strong substitutability between capital and energy ($MES_{KE} = 3.66$) suggests that policies to reduce the cost of capital would be particularly effective at improving energy efficiency. Specific policies include:

- **Investment incentives:** Tax credits, accelerated depreciation, and low-interest loans for energy-efficient capital investments.
- **Technology transfer:** Facilitating the import and diffusion of efficient technologies.
- **Energy management:** Supporting firms in implementing energy management systems and best practices.

Addressing Labor Implications:

The complementarity between capital and labor ($MES_{KL} = -1.94$) suggests that capital investment creates demand for complementary labor, particularly skilled workers. This implies:

- **Skills Training:** Investment in technical and vocational education to ensure a supply of skilled workers.
- **Labor Market Policies:** Reducing rigidities that might prevent firms from hiring the skilled workers they need.
- **Social Protection:** Supporting workers who are displaced by technological change, even though displacement may be less than feared.

Energy Pricing and Subsidy Reform:

The substitution elasticities suggest that energy price increases (e.g., through subsidy removal) would:

- Encourage capital deepening and energy efficiency improvement.
- Potentially increase employment (through energy-labor substitution).
- Have manageable negative impacts on output (given the relatively modest direct effect of energy intensity on output).
- However, the asymmetry result suggests that the transition should be managed carefully to avoid sudden efficiency declines.

Power Sector Reform and Infrastructure:

The positive impact of the 2013 power sector reform on energy efficiency suggests that continuing reforms in the electricity sector is crucial. Specific recommendations include:

- **Distribution Efficiency:** Reducing technical and commercial losses.
- **Generation Capacity:** Increasing supply reliability.
- **Tariff Reform:** Moving toward cost-reflective tariffs while protecting vulnerable consumers.
- **Off-Grid Solutions:** Supporting decentralized energy solutions for manufacturing firms.

Sectoral Targeting:

Given the differences between sub-sectors (e.g., energy-intensive vs. labor-intensive), policies should be tailored to specific sub-sectors. The SFA results suggest that labor-intensive sectors have higher energy intensity, while capital-intensive sectors have lower energy intensity. This implies:

- **Targeted Support:** Providing technical assistance and financing to labor-intensive sectors to improve their energy efficiency.
- **Sectoral Composition:** Considering energy efficiency in industrial policy decisions about which sectors to promote.
- **Best Practices:** Disseminating best practices from energy-efficient sectors to other sectors.

Limitations and Future Research Directions

This study has several limitations that suggest avenues for future research:

- **Aggregate Data Limitations:**

The use of aggregate sector-level data masks heterogeneity across firms and sub-sectors. Future

research could use firm-level data (if available) to examine the determinants of energy efficiency at the micro level and test whether the asymmetric relationships hold at the firm level.

- **Data Quality and Measurement:**

The quality of Nigerian manufacturing data is a concern, with potential measurement errors in variables such as capital stock and energy consumption. Future research could improve measurement by collecting primary data or using alternative data sources (e.g., satellite imagery for industrial activity).

- **Endogeneity and Causality:**

While we use SFA and NARDL to address some endogeneity concerns, there may still be omitted variable bias. Future research could use instrumental variable approaches or quasi-experimental designs to identify causal effects.

- **Temporal and Structural Breaks:**

Our analysis assumes that the relationships are stable over time, but structural breaks may have occurred. Future research could explore time-varying parameters or regime-switching models.

- **Environmental and Climate Dimensions:**

This study focuses on productivity effects, but energy efficiency also has environmental and climate implications. Future research could integrate environmental outcomes (e.g., CO₂ emissions) into the analysis to examine the co-benefits and trade-offs of energy efficiency policies.

- **Distributional and Equity Implications:**

The analysis focuses on aggregate manufacturing output, but the benefits of energy efficiency may be distributed unequally across firms and workers. Future research could examine distributional and equity implications, including effects on small vs. large firms, formal vs. informal sector, and different worker categories.

- **International Comparisons:**

While we compare our findings to those from other countries, a more systematic cross-country comparative analysis would provide valuable insights into the generalizability of the findings and the role of specific contextual factors.

Conclusion

This study has provided a comprehensive analysis of the energy-productivity nexus in Nigeria's manufacturing sector from 1981 to 2023. Using a three-pronged methodological approach Stochastic Frontier Analysis

for efficiency estimation, Nonlinear Autoregressive Distributed Lag modeling for asymmetry analysis, and Translog cost function with Morishima Elasticities for substitution analysis we have uncovered several novel findings with important policy implications. The SFA results reveal that the sector operates at an average energy efficiency of only 82.2%, indicating a substantial efficiency gap. Capital investment and the 2013 power sector reform have been important drivers of efficiency improvement, while labor input is associated with higher energy intensity. The NARDL results demonstrate a significant and asymmetric impact of energy efficiency on manufacturing output: positive efficiency improvements boost output by 0.93%, but negative efficiency declines reduce output by 2.24% approximately 2.4 times greater in magnitude. This "risk asymmetry" means the sector is far more vulnerable to efficiency losses than it is benefited by equivalent gains. The Translog cost function estimates reveal that capital and energy are strong substitutes ($MES_{KE} = 3.66$), while capital and labor are complements ($MES_{KL} = -1.94$), suggesting that energy price increases would encourage capital investment and skills upgrading. These findings challenge the conventional view that energy efficiency is merely an environmental or cost-saving concern. Instead, they demonstrate that energy efficiency is a strategic determinant of industrial productivity in Nigeria. The asymmetry result is particularly important, as it suggests that preventing efficiency declines should be a higher policy priority than promoting efficiency improvements. The substitution patterns indicate that market-based instruments (energy pricing, capital incentives) can be effective tools for improving efficiency, but they must be accompanied by complementary policies (skills training, social protection) to address the labor implications. By addressing the energy-productivity nexus with these nuanced, evidence-based strategies, Nigeria can unlock sustainable industrial growth, enhancing both economic resilience and environmental sustainability. The study contributes to the literature by providing rigorous empirical evidence from a Sub-Saharan African context, demonstrating methodological innovations in the use of SFA, NARDL, and MES, and offering policy-relevant insights that can inform Nigeria's industrial and energy policies.

References

1. International Renewable Energy Agency (IRENA).

- (2023). Renewable energy and jobs: Annual review 2023. Abu Dhabi: IRENA <https://www.iea.org/reports/renewables-2023>.
2. National Bureau of Statistics (NBS). (2011, 2014, 2018, 2021, 2024). Annual abstract of statistics. Federal Republic of Nigeria <https://www.nigerianstat.gov.ng/elibrary/read/187>.
 3. Worrell E, Laitner JA, Ruth M, Finman H (2003) Productivity benefits of industrial energy efficiency measures. *Energy* 28 :1081-1098.
 4. Subrahmanya MHB (2006) Energy efficiency and economic performance: A case study of small-scale bricks and foundry clusters in India. *Energy Policy* 34: 3836-3845.
 5. Cantore N, Calì M, te Velde DW (2016) Does energy efficiency improve technological change and economic growth in developing countries ? *Energy Policy* 92: 279-285.
 6. Haider A, Ganie AG (2017) Energy efficiency and total factor productivity : Evidence from Indian manufacturing. *Energy Efficiency* 10:1171-1186.
 7. Montalbano P, Nenci S (2019) Energy efficiency, productivity and exporting: Firm-level evidence from Latin America. *Energy Economics* 79: 97-110.
 8. Atoyebi KO (2023) Energy efficiency and economic growth in selected Sub-Saharan African countries. *Journal of Economic Studies* 5:120-135.
 9. Haller SA, Hyland M (2014) Energy-related technological change and energy efficiency in Ireland. *The Energy Journal* 35: 1-26.
 10. Zha D, Ding N (2014) Elasticities of substitution between energy and non-energy inputs in China. *Energy Economics* 44:288-295.
 11. Debreu G (1951) The coefficient of resource utilization. *Econometrica* 19:273-292.
 12. Farrell MJ (1957) The measurement of productive efficiency. *Journal of the Royal Statistical Society: Series A (General)* 120: 253-281.
 13. Jaffe AB, Stavins RN (1994) The energy-efficiency gap: What does it mean? *Energy Policy* 22: 804-810.
 14. Jovanovic B (1982) Selection and the evolution of industry. *Econometrica* 50: 649-70.
 15. Popper KR (1959) *The Logic of Scientific Discovery*. London: Hutchinson <https://www.routledge.com/The-Logic-of-Scientific-Discovery/Popper/p/book/9780415278447>.
 16. Harberger AC (1978) Perspectives on capital and technology in less developed countries. In M. J. Artis & A. R. Nobay (Eds.), *Contemporary Economic Analysis*. London: Croom Helm <https://www.econbiz.de/Record/perspectives-on-capital-and-technology-in-less-developed-countries-harberger-arnold/10002652784>.
 17. Granger CWJ, Newbold P (1974) Spurious regressions in econometrics. *Journal of Econometrics* 2:111-120.
 18. Zivot E, Andrews DWK (1992) Further evidence on the great crash, the oil-price shock, and the unit-root hypothesis. *Journal of Business & Economic Statistics* 10: 251-270.
 19. Aigner D, Lovell CAK, Schmidt P (1977) Formulation and estimation of stochastic frontier production function models. *Journal of Econometrics* 6:21-37.
 20. Meeusen W, van den Broeck J (1977) Efficiency estimation from Cobb-Douglas production functions with composed error. *International Economic Review* 18: 435-444.
 21. Jondrow J, Lovell CAK, Materov IS, Schmidt P (1982) On the estimation of technical inefficiency in the stochastic frontier production function model. *Journal of Econometrics* 19: 233-238.
 22. Shin Y, Yu B, Greenwood-Nimmo M (2014) Modelling asymmetric cointegration and dynamic multipliers in a nonlinear ARDL framework. In *Festschrift in Honor of Peter Schmidt* New York: Springer 281-314
 23. Pesaran, MH, Shin Y, Smith RJ (2001) Bounds testing approaches to the analysis of level relationships. *Journal of Applied Econometrics* 16: 289-326.
 24. Christensen LR, Jorgenson DW, Lau LJ (1973) Transcendental logarithmic production frontiers. *The Review of Economics and Statistics* 55:28-45.
 25. Blackorby C, Russell RR (1989) Will the real elasticity of substitution please stand up? (A comparison of the Allen/Uzawa and Morishima elasticities). *The American Economic Review* 79: 882-888.
 26. Park S, Kim J (2018) Energy efficiency and productivity in South Korean manufacturing. *Energy Economics* 72: 476-485.