THE PRODUCTIVITY-ENERGY NEXUS IN NIGERIA: ASYMMETRIC IMPACTS OF EFFICIENCY AND FACTOR SUBSTITUTION

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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 asymmetrically affects manufacturing output, 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.

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

INTRODACTION

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 Worrell et al. (2003), Subrahmanya (2006), and Cantore et al. (2016) find that energy efficiency enhances productivity, others, such as Haider and Ganie (2017), report a negative relationship, suggesting context-specific dynamics [3], [4], [5], [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

The study is grounded in production theory [11], [12] and the neoclassical theory of the firm. It incorporates the Energy Efficiency Gap theory (Jaffe & Stavins, 1994) and Jovanovic's (1982) theory of firm selection to explain variations in efficiency [13], [14]. The post-positivist research design employs quantitative, non-experimental methods on secondary time-series data (1981–2023) from the Central Bank of Nigeria (CBN), National Bureau of Statistics (NBS), and World Bank.

Model Specification

Objective 1: Estimating Energy Efficiency

While Debreu introduced the estimation of technical efficiency using an output-oriented approach, Farrell established the measurement of technical efficiency through an input-oriented approach. Based on feasibility, this study adopted the input-oriented approach of the stochastic frontier analysis to estimate energy efficiency (EE) given energy intensity (EI), manufacturing output (MO) and the input of capital (CAP), labour (LAB) and a dummy policy variable (PDUM) capturing the dissolution of The Power Holding Company of Nigeria (PHCN) and the privatization of six generating companies and ten distribution companies

We adopt an input-oriented Stochastic Frontier Analysis (SFA) model [15] to estimate energy efficiency (EE), distinguishing between inefficiency and random noise. The model is specified as:

$$lnEI_t = \beta_0 + \beta_1 lnMO_t + \beta_2 lnCAP_t + \beta_3 lnLAB_t + \beta_4 POLDUM_t + \vartheta_t + \mu_t$$

where EI is energy intensity, MO is manufacturing output, CAP is capital input, LAB is labor input, POLDUM is a dummy for the 2013 power sector reform, ϑ_t is random noise, and μ_t is the inefficiency term.

Objective 2: Assessing the Impact on Productivity

Several econometric techniques are available for estimating energy efficiency and its impacts on Nigeria's manufacturing sector. However, 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 a non-stationary series can yield misleading results. This is referred to as "spurious regression". As such, among other tests, unit-root tests were conducted on all the data to guide against spurious regression results.

To capture asymmetric effects, we employ a Nonlinear Autoregressive Distributed Lag (NARDL) model [16]. The NARDL was employed to estimate the asymmetric relationships between energy efficiency and manufacturing output performance (productivity). This model

captures both short-run and long-run asymmetries, allowing for the examination of distinct positive and negative effects of energy efficiency on manufacturing output.

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

where EE^{+} and EE^{-} are partial sum decompositions of positive and negative changes in energy efficiency, and ECM is the error correction term.

Objective 3: Analyzing Input Substitution

The manufacturing sector plays a dynamic role in Nigeria's economic development, and understanding the relationships between its inputs is crucial for informed decision-making. One key aspect of this is the substitutability between energy and non-energy inputs, including labor and capital. The objective herein investigates energy and non-energy input substitution possibilities in Nigeria's manufacturing sector using the translog cost function, focusing on the Morishima Elasticity of Substitution (MES).

The translog cost function provides a flexible framework for estimating the relationship between input and output in a production process. By analyzing the total manufacturing cost (C) in relation to labor price (PL), price of capital (Pk) proxied by the maximum lending rate, and energy price (Pe), we can estimate the MES between these inputs. The MES measures the percentage change in the ratio of two inputs in response to a percentage change in the price of one of the inputs, holding output and other input prices constant.

The analysis utilized input shares, including energy share (ES), labor share (LS), and capital share (CS), to calculate the MES between energy and non-energy inputs. Real manufacturing output (MO) was also considered to account for the impact of output levels on input demand. The findings of this analysis will have significant implications for Nigeria's manufacturing sector. For instance, if energy and non-energy inputs are found to be substitutes, firms may be able to adjust their input mix in response to changes in input prices, which could have important implications for energy policy and industrial development. Conversely, if inputs are found to be complements, firms may need to adopt a more integrated approach to input management. However, it could be possible for inputs to be independent of one another.

A Translog cost function [17] is estimated via Iterated Seemingly Unrelated Regression (iSUR):

$$ln\left(\frac{C}{P_L}\right) = \alpha_0 + \sum_i \delta_i \, ln\left(\frac{P_i}{P_L}\right) + \frac{1}{2}\sum_i \sum_j \alpha_{ij} \, ln\left(\frac{P_i}{P_L}\right) ln\left(\frac{P_j}{P_L}\right) + \tau lnMO + \theta T$$

for i, j = K, E. From the estimated parameters, we compute the Morishima Elasticity of Substitution (MES) [18]:

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

Data Source and Type

The study utilized secondary time-series data. Data sourced from publicly available and reputable institutions to ensure reliability and validity. The data covered the period from 1981 to 2023. This timeframe is chosen as it captures significant periods of oil price volatility, structural adjustment programs, and recent power sector reforms in Nigeria, providing a rich context for analysis.

Table 1. Definition and Measurement of Variable

Variable Category	Variable Name	Symbol	Measurement
Dependent Variables	Manufacturing Output	MO	Total annual sales/value of output (NGN)
	Energy Intensity	EI	Total cost of energy / Manufacturing Output
	Total Manufacturing Cost	C	Sum of capital, labour, and energy costs (NGN)
Independent Variables	Capital Input	CAP	Total value of machinery and equipment (NGN)
	Labour Input	LAB	Total wages paid to employees (NGN)
	Energy Input	E	Total cost of electricity and fuel (NGN)
	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)
	Price of Labour	P_L	Mean wage earnings per employee
	Price of Energy	P_E	Weighted average cost per tonne of oil equivalent (TOE)
Policy Variable	Power Sector Reform Dummy	POLDUM	Dummy variable: 0 for years before 2013, 1 for 2013 and after

RESULTS AND DISCUSSION

Energy Efficiency Trends

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. The likelihood ratio test (LR = 7.44, p = 0.003) confirms the presence of significant technical inefficiency. Capital investment (β = -1.213, p = 0.000) and the 2013 power sector reform (β = -1.669, p = 0.000) were associated with reduced energy intensity (improved efficiency), while labor input increased it (β = 2.134, p = 0.000).

Table 2: Stochastic Frontier Analysis Results

Variable	Coefficient	Std. Error	p-value
Constant	-39.165	0.0003	0.000
ln_MO	2.284	0.00001	0.000
ln_CAP	-1.213	0.00002	0.000
ln_LAB	2.134	0.00002	0.000
POLDUM	-1.669	0.00001	0.000
σ_μ	0.716	0.077	-
σ_θ	1.58e-08	3.50e-06	-
Lambda	4.54e+07	-	-

The SFA model estimation slope coefficients shown in Table 2 above indicate that manufacturing output (MO) yielded a significant and positive impact on energy intensity (EI), with a coefficient of 2.2841. This implies that a 1% increase in output would lead to a 2.28% increase in output, ceteris paribus. The *p*-value of 0.000 indicates that this relationship is highly significant. This finding suggests that as the manufacturing sector produces more output, it requires more energy per unit of output. The changes in capital (CAP) yielded a negative and significant impact on energy intensity (EI), having a partial slope coefficient of -1.2126 and a corresponding *p*-value = 0.000. The foregoing implies that as capital increases, energy intensity decreases significantly;

thus, increased investment in capital leads to more energy-efficient production processes. In contrast, labour has a significant and positive impact on energy intensity (EI), with a slope coefficient of 2.134 and a p-value of 0.000. This suggests that a 1% increase in labour would lead to a 2.13% increase in energy intensity (EI), ceteris paribus. The foregoing suggests that increased labour input may lead to less energy-efficient production processes. Policy Dummy (*POLDUM*), with a slope coefficient of -1.669, indicates a negative relationship between the policy dummy variable and energy intensity. The restructuring of the power sector in 2013 (captured by the dummy variable) is associated with a decrease in energy intensity. This suggests that the policy change had a positive impact on energy efficiency in the manufacturing sector. The *p*-value (0.000) indicates that this relationship is statistically significant.

Asymmetric Impact on Manufacturing Output

The NARDL model (AIC = -5.6623) confirms a long-run cointegrating relationship (Bounds test F = 9.0357). The results demonstrate a significant but **asymmetric** impact. In the long run, a 1% increase in energy efficiency raises manufacturing output by 0.93% (φ^+ = 0.9346, p = 0.012), while a 1% decrease reduces output by 2.24% (φ^- = 2.2447, p = 0.018). The symmetry test rejects the null hypothesis for the long run (F = 11.6125, p = 0.002), confirming the presence of asymmetry. This implies that the sector is more vulnerable to efficiency declines than it benefits from improvements, a critical insight for risk management.

The NARDL model (optimal lag structure: 1,1,1,1,1,1 based on AIC) confirms cointegration (Bounds test F-statistic = 9.0357 > I(1) critical value at 1%). The error correction term is negative and significant (γ = -0.194, p = 0.000), indicating convergence to long-run equilibrium.

Long-run asymmetry is evident in the differential coefficients for positive versus negative efficiency changes. A 1% improvement in energy efficiency increases TFP by 0.93% (θ^+ = 0.9346\), p = 0.012), while a 1% deterioration decreases TFP by 2.24% (θ^-= 2.2447), p = 0.018)—approximately 2.4 times greater in magnitude. This asymmetry is statistically confirmed by the long-run symmetry test (F = 11.6125, p = 0.002).

Short-run dynamics also reveal asymmetry, though less pronounced. Immediate responses to efficiency changes show similar directional effects but smaller magnitudes. The joint symmetry test confirms overall asymmetry (F = 5.9976, p = 0.007).

Table 3: NARDL Model Results - Long-run Coefficients

Variable	Coefficient	Std. Error	p-value
EE^+	0.9346	0.3662	0.012
EE^-	2.2447	0.9321	0.018
CAP	0.9839	0.1845	0.000
LAB	-0.9627	0.2743	0.001
EI	-0.2609	0.0782	0.001
POLDUM	0.6376	0.5821	0.278
Trend	0.0315	0.0201	0.124

Input Substitution Possibilities

The Translog cost function estimates fit well (R^2 = 0.9934). The computed Morishima Elasticities reveal distinct input relationships:

- Capital and Energy are Substitutes: MES_{KE} averages 3.66, indicating that a rise in energy price would lead to a significant increase in the capital/energy ratio.
- Energy and Labor are Substitutes: MES_{EL} averages 2.32.

- Capital and Labor are Complements: MES_{KL} averages -1.94, suggesting that capital deepening accompanies increased skilled labor demand.

The MES results (Table 3) reveal more nuanced and policy-relevant relationships.

Table 4: 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_EL	2.318	0.275	1.927	2.714	**Substitutes**
MES_KL	-1.937	0.432	-2.484	-1.165	**Complements**

The positive MES for capital-energy (3.66) indicates that a 1% increase in energy price would increase the capital-energy ratio by approximately 3.66%, suggesting strong substitution potential. Similarly, the energy-labor MES (2.32) indicates substitution possibilities, though less pronounced. The negative MES for capital-labor (-1.94) reveals complementarity, implying that capital deepening is associated with increased skilled labor demand rather than labor displacement.

CONCLUSION AND POLICY IMPLICATIONS

This study on Nigeria's manufacturing sector (1981–2023) reveals three key findings:

1. **Significant Energy Efficiency Gap**: The sector operates at an average energy efficiency of only 82.2%, indicating substantial room for improvement. The 2013 power sector reforms and increased capital investment were found to improve efficiency, while labor input was associated with higher energy intensity.
2. **Asymmetric Impact on Productivity**: Energy efficiency has a disproportionate effect on manufacturing output. While a 1% improvement in efficiency boosts output by 0.93%, a 1% decline reduces output by a much larger 2.24%. This "risk asymmetry" means the sector is far more vulnerable to efficiency losses than it is benefited by equivalent gains.
3. **Clear Input Substitution Possibilities**: The analysis confirms that capital and energy are strong substitutes. This means rising energy prices would likely incentivize a shift toward more capital-intensive, energy-efficient technologies. However, capital and labor were found to be complements, suggesting that such technological upgrades would increase the demand for skilled labor rather than replace workers.

Policy recommendations include:

1. Integrate energy efficiency into core industrial policy, offering targeted fiscal incentives for audits, retrofits, and adoption of efficient technologies.
2. Ensure stable energy pricing and supply to reduce uncertainty and encourage long-term investments in efficiency.
3. Develop skills training programs aligned with the technological upgrading prompted by energy policies, addressing the capital-labor complementarity.
4. Utilize Morishima Elasticities in modeling the economic impact of energy price reforms to anticipate shifts in factor demand accurately.

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.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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