

# The Asymmetric Nexus: Energy Efficiency and Total Factor Productivity in Nigeria's Manufacturing Sector

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## ABSTRACT

This study examines the dynamic, non-linear relationship between energy efficiency and total factor productivity (TFP) in Nigeria's manufacturing sector from 1981 to 2023. Using a novel combination of Stochastic Frontier Analysis (SFA) and a Nonlinear Autoregressive Distributed Lag (NARDL) model, we uncover an asymmetric nexus in which improvements and deteriorations in energy efficiency have differential impacts on sectoral performance. Our findings reveal an average energy efficiency score of 82.2%, indicating significant potential for improvement. Crucially, we demonstrate that while efficiency gains positively influence TFP, efficiency losses exert a disproportionately larger negative effect—approximately 2.4 times greater in magnitude. These results challenge conventional symmetric assumptions in production theory and carry substantial implications for industrial policy in energy-dependent developing economies. We argue that energy efficiency should be reconceptualized as a strategic determinant of industrial competitiveness rather than merely a cost-containment measure.

**Keywords:** Energy Efficiency, Total Factor Productivity, Asymmetric Effects, Nigerian Manufacturing, Stochastic Frontier Analysis, NARDL Model, Industrial Policy

## INTRODUCTION

Energy constitutes both a critical input and a significant cost component in manufacturing, accounting for approximately 40% of production overhead in Nigerian firms (Asaleye et al., 2018; Sheu & Taiwo, 2025). Despite this substantial expenditure, the manufacturing sector's contribution to Nigeria's Gross Domestic Product (GDP) has declined from 11.75% in 2011 to 7.61% in 2024 (NBS, 2011; 2024), even as energy consumption has increased by 91.1% for petroleum products and 48.6% for electricity during 2010-2022 (NBS, 2014; 2023). This paradoxical relationship—rising energy use alongside stagnant sectoral performance—raises fundamental questions about the efficiency with which energy is converted into economic output.

Theoretical literature presents divergent perspectives on the energy efficiency-productivity nexus. Neoclassical production theory suggests that efficiency improvements should enhance productivity through cost reduction and technological advancement (Solow, 1956). However, empirical evidence remains contested, with studies reporting positive (Worrell et al., 2003; Cantore et al., 2016), negative (Haider & Ganie, 2017), or insignificant (Pons et al., 2013) relationships. This ambiguity suggests potential non-linearities and contextual specificities that conventional symmetric models may overlook.

In Nigeria, empirical research on this relationship is limited, with studies predominantly focusing on simple intensity measures or partial productivity indicators (Adenikinju & Alaba, 2010; Tijani, 2022). This study addresses three critical gaps: (1) the application of frontier efficiency measurement techniques to capture true technical efficiency; (2) the examination of potential asymmetries in the efficiency-productivity relationship;

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and (3) the use of total factor productivity (TFP) as a comprehensive performance measure that accounts for all inputs simultaneously.

## Theoretical Framework and Methodology

### Theoretical Foundation

This study integrates multiple theoretical perspectives. The Energy Efficiency Gap theory (Jaffe & Stavins, 1994) explains suboptimal adoption of efficiency despite potential benefits. Jovanovic's (1982) theory of firm selection provides insight into efficiency differentials across firms of varying size and age. Neoclassical production theory (Solow, 1956) offers the foundational framework for understanding input-output relationships. We extend these frameworks by hypothesizing asymmetric responses—that improvements and deteriorations in energy efficiency may have differential impacts on productivity due to adjustment costs, irreversible investments, and institutional rigidities.

### Data and Variables

We utilize annual time-series data for Nigeria's manufacturing sector from 1981-2023. Manufacturing output (MO) represents real value added. Energy efficiency (EE) is derived from Stochastic Frontier Analysis. Total factor productivity (TFP) is calculated using the Levinsohn-Petrin (2003) algorithm, which controls for simultaneity bias in input choices. Control variables include capital stock (CAP), labor input (LAB), energy intensity (EI), and a policy dummy (POLDUM) capturing the 2013 power sector reforms. Capital (CAP) and labor (LAB) are included as core inputs in the production function. Energy intensity (EI) is controlled to isolate the pure efficiency effect from scale effects. The policy dummy (POLDUM) captures structural breaks from sector reforms.

### Empirical Strategy

#### Stage 1: Estimating Energy Efficiency

We employ an input-oriented Stochastic Frontier Analysis (SFA) model:

$$\ln EI_t = \beta_0 + \beta_1 \ln MO_t + \beta_2 \ln CAP_t + \beta_3 \ln LAB_t + \beta_4 POLDUM_t + \vartheta_t + \mu_t$$

where EI represents energy intensity,  $\vartheta_t \sim N(0, \sigma_\vartheta^2)$  captures random noise, and  $\mu_t \sim N^+(0, \sigma_\mu^2)$  represents technical inefficiency. Technical inefficiency is captured by the one-sided error term  $\mu_t$ . We then compute the energy efficiency score for year t as  $EE_t = \exp(-\beta\mu_t)$ , which ranges from 0 to 1, with 1 representing full efficiency.

#### Stage 2: Modeling the Asymmetric Relationship

To capture potential asymmetries, we employ a Nonlinear ARDL (NARDL) model (Shin et al., 2014):

$$\Delta TFP_t = \alpha_0 + \sum_{i=1}^p \varphi_i \Delta TFP_{t-i} + \sum_{i=0}^q \beta_i^+ \Delta EE_{t-i}^+ + \sum_{i=0}^q \beta_i^- \Delta EE_{t-i}^- + \gamma ECM_{t-1} + \varepsilon_t$$

where  $EE^+$  and  $EE^-$  represent partial sum decompositions of positive and negative changes in energy efficiency, respectively:

$$EE_t^+ = \sum_{j=1}^t \max(\Delta EE_j, 0), \quad EE_t^- = \sum_{j=1}^t \min(\Delta EE_j, 0)$$

The error correction term  $ECM_{t-1}$  captures long-run equilibrium adjustment.

## RESULTS AND ANALYSIS

### Energy Efficiency Estimates

The SFA results (Table 1) reveal significant technical inefficiency in Nigeria's manufacturing sector ( $\sigma_\mu = 0.7162$ , LR test = 7.44,  $p = 0.003$ ). The average energy efficiency score across the period is 0.822 (82.2%), with a standard deviation of 0.151, indicating substantial variability and room for improvement. Capital investment demonstrates a significant negative relationship with energy intensity ( $\beta = -1.213$ ),  $p = 0.000$ ), suggesting capital-energy complementarity in efficiency enhancement. The 2013 power sector reform shows a significant efficiency-improving effect ( $\beta = -1.669$ ),  $p = 0.000$ ).

Table 1: 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
$\sigma_\mu$	0.716	0.077	-
$\sigma_\theta$	1.58e-08	3.50e-06	-
Lambda	4.54e+07	-	-

\* p-value for the one-sided variance parameter is not standard

### Asymmetric Impact on Total Factor Productivity

The NARDL model (optimal lag structure: 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 ( $\gamma = -0.194$ ,  $p = 0.000$ ), 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% ( $\theta^+ = 0.9346$ ),  $p = 0.012$ ), while a 1% deterioration decreases TFP by 2.24% ( $\theta^- = 2.2447$ ),  $p = 0.018$ )—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 2: NARDL Model Results - Long-run Coefficients

Variable	Coefficient	Std. Error	p-value
EE <sup>+</sup>	0.9346	0.3662	0.012

EE <sup>-</sup>	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

## DISCUSSION AND IMPLICATIONS

### Theoretical Implications

Our findings challenge the conventional assumption of symmetry in production theory. The disproportionate impact of efficiency deterioration suggests **hysteresis effects**—where losses create persistent negative trajectories that are difficult to reverse. This aligns with theories of organizational rigidity and sunk costs, where efficiency declines may signal deeper systemic failures beyond mere input misallocation.

The results also extend the **Energy Efficiency Gap** framework by quantifying not just the existence of sub-optimal efficiency but its dynamic consequences. The 18% average efficiency gap represents not merely foregone cost savings but significant unrealized productivity potential.

### Policy Implications

The asymmetric relationship carries crucial policy implications:

- Preventive Policy Focus:** Given the disproportionate damage from efficiency deterioration, policies should prioritize preventing backsliding as much as promoting improvements. This suggests regulatory frameworks with minimum efficiency standards and monitoring mechanisms.
- Risk-Asymmetric Investment Incentives:** The 2.4:1 asymmetry ratio suggests that the social returns to preventing efficiency losses exceed those from achieving equivalent gains. Investment incentives should reflect this risk asymmetry, potentially through insurance mechanisms or guaranteed buy-back programs for efficiency-enhancing equipment.
- Integrated Energy-Industrial Policy:** The significant efficiency gains from the 2013 power sector reform ( $\beta = -1.669$ ) demonstrate that energy policy is industrial policy. Future reforms should explicitly target manufacturing efficiency through dedicated programs, technical assistance, and targeted subsidies.
- Dynamic Performance Metrics:** Conventional productivity metrics that assume symmetric responses may underestimate the true cost of efficiency deterioration. Policymakers should incorporate asymmetric assessment frameworks in project evaluation and policy impact analysis.

## CONCLUSION

This study reveals a fundamentally asymmetric relationship between energy efficiency and total factor productivity in Nigeria's manufacturing sector. Efficiency deteriorations exert approximately 2.4 times greater negative impact on productivity than equivalent improvements provide in positive benefits. This asymmetry challenges conventional production theory and carries significant implications for industrial policy in energy-dependent developing economies.

The findings suggest that energy efficiency should be reconceptualized from a cost-containment measure to a strategic determinant of industrial resilience. Policies must account for the disproportionate risks of efficiency deterioration and develop mechanisms to prevent backsliding while promoting improvements.

Future research should explore the micro-foundations of this asymmetry through firm-level studies and examine whether similar patterns exist in other developing country contexts. Additionally, research should investigate the specific channels through which efficiency deteriorations create persistent negative effects, including potential impacts on workforce skills, maintenance cultures, and technological lock-in. While our model controls for key factors, future firm-level studies could incorporate additional variables such as R&D intensity and managerial quality to unpack the channels of asymmetry further.

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