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# **The Asymmetric Effect of Financial Development on Energy Consumption: NARDL Evidence from 173 Selected Countries**

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## Abstract

**Purpose:** This study examines the asymmetric relationship between financial development (FD) and energy consumption (EC) across 173 economies from 1990 to 2019. It assesses whether positive and negative FD shocks affect EC differently and how these effects vary by income group, informing decisions that balance financial deepening and sustainable energy use.

**Design/methodology/approach:** A Nonlinear Autoregressive Distributed Lag (NARDL) framework is applied to a balanced panel of 56 high-income, 45 upper-middle-income, 50 lower-middle-income, and 22 low-income countries. FD is measured using the IMF Financial Development Index and decomposed into financial market development (FMD) and financial institution development (FID), with urbanisation and GDP per capita as controls. Positive and negative FD shocks are modeled via partial-sum processes, and pooled mean group estimators with Wald tests identify short- and long-run asymmetries.

**Findings:** Globally, positive shocks in overall FD and FMD reduce EC, whereas negative shocks in FD, FMD, and FID increase it. Heterogeneity is substantial: in high- and lower-middle-income economies, both positive and negative shocks to FD, FMD, and FID generally raise EC, while in upper-middle- and low-income economies, FMD tends to reduce EC under both shock types. Asymmetric effects are strongest for FD and FMD, with FID asymmetry concentrated in high-income countries. This income-specific FID asymmetry can be explained by the maturity and depth of financial institutions in advanced economies: in high-income countries, institutional development is sophisticated enough that positive and negative credit shocks transmit asymmetrically into energy investment decisions ( $W_{LR} = 13.61$ ,  $p < 0.01$ ). By contrast, in upper-middle-, lower-middle- and low-income economies, financial institutions remain underdeveloped relative to market size, and both positive and negative FID shocks produce broadly symmetric EC responses ( $W_{LR}$  values of 0.08, 1.50 and 0.59 respectively, all non-significant), reflecting a more homogeneous credit-transmission mechanism regardless of shock direction.

**Research limitations/implications:** The estimates may not fully capture recent structural breaks in financial systems, technology, or energy policy. Notably, the dataset ends in 2019 and therefore excludes the substantial disruptions of the COVID-19 pandemic period (2020–2022), including unprecedented credit contractions, energy price volatility, and large-scale green fiscal stimulus packages, which may have altered the FD–EC relationship in important ways. Future work could extend the sample to cover this period and incorporate sectoral EC, green-finance indicators, and higher-frequency financial data.

**Practical implications:** Results suggest that steady financial deepening can curb EC, whereas contractions in FD may sharply increase it, especially in bank-dominated systems. Income-specific financial and energy policies are needed to manage these asymmetric effects.

**Originality/value:** This study is among the first to apply a global NARDL framework with the IMF FD index to model positive and negative FD, FMD, and FID shocks across 173 economies, linking asymmetric FD–EC dynamics to decision-relevant policy design.

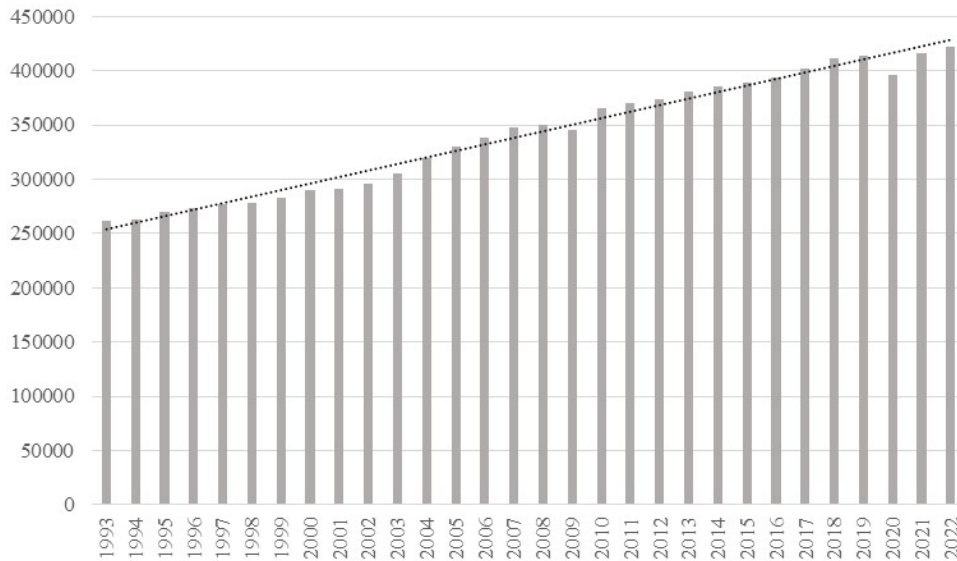
**Keywords:** Financial development; Energy consumption, Financial market development, Financial institution development, Asymmetric effect, NARDL.

**JEL Classifications:** E44, O13.

# 1. Introduction

The intricate relationship between financial development (FD) and energy consumption (EC) has garnered significant attention from researchers and policymakers striving to balance economic growth and sustainability. FD, defined as the expansion and sophistication of financial markets and institutions, facilitates economic activities by improving capital access, reducing transaction costs, and promoting investment (Ma & Fu, 2020; Sarwar et al., 2021; Tran, 2023). Concurrently, EC remains a cornerstone of economic growth, powering industrial and household activities (Gershon et al., 2024; Nguyen et al., 2023; Wenhui et al., 2025). According to a report by Bacon and Kojima (2016), EC directly correlates with poverty reduction and GDP growth. Countries with high EC levels tend to experience faster economic growth and higher per capita income. Global EC has increased in tandem with economic growth. For instance, the International Energy Agency (IEA) reported in 2023 that global EC has grown at an annual rate of about 1.6% over the past three decades, with further increases anticipated.

**Figure 1.** Total final consumption in petajoules (PJ) in the world



(Source: IEA, 2023)

Figure 1 reveals an upward trend in the observed energy consumption from 1993 to 2022. Although there are minor fluctuations from year to year, highlighting gradual yet consistent growth. It highlights the need to explore the dynamics of final consumption through long-term estimates to capture both linear and asymmetric dynamics over extended periods. In this context, fossil fuels dominate the energy mix, accounting for over 68% of the global supply, while the industrial, transport, and residential sectors collectively account for approximately 79% of the energy utilisation. Although EC is integral to economic progress (Esen & Bayrak, 2017; Jia et al., 2023), its reliance on fossil fuels exacerbates environmental issues, notably CO<sub>2</sub> emissions and other greenhouse gases, intensifying climate change and ecological degradation (Mitić et al., 2023; Nguyen et al., 2024). Thus, understanding this relationship is critical for

addressing development goals, as economic growth must be balanced through efforts to mitigate climate change and reduce carbon emissions (Alper et al., 2023; Gahlot & Garg, 2024).

Transitioning to clean and sustainable energy sources is vital for long-term growth, avoiding resource depletion and preserving environmental integrity (Bello et al., 2024). Achieving this shift requires significant financial resources. Global estimates suggest investment needs of about US\$4 trillion annually for renewable energy, storage infrastructure, and decarbonisation technologies to reach net-zero emissions (IEA, 2023). Thus, FD has emerged as an important factor of this transformation, facilitating access to innovative instruments, such as green bonds, carbon credits, and renewable energy investment funds (Bhutta et al., 2022; Tang et al., 2024). Such mechanisms are critical for achieving sustainable development goals and mitigating climate change's adverse effects. However, the relationship between FD and EC is complex and often nonlinear, influenced by factors such as development level, technological progress, and financial shocks (Boufateh & Saadaoui, 2020; Rehman et al., 2023; Thebuho et al., 2022). FD fosters energy-efficient technologies and renewable energy investments, reducing the carbon footprint of economic activities (Akpanke et al., 2024; Liu et al., 2022). FD's green financial systems target technological diffusion, clean energy, and the adoption of energy-efficient technologies that can reduce energy intensity (Quang & Thao, 2022; Yu et al., 2022). Conversely, FD can increase EC through mechanisms such as the "wealth effect", enabling consumers to finance energy-intensive products and encouraging businesses to scale operations using cheaper capital (Alshagri et al., 2024; Nguyen et al., 2022). Financial systems that support energy-intensive industries can exacerbate environmental challenges (Achuo et al., 2024; Adeneye et al., 2023). This duality emphasises the need for context-specific analyses to understand the net impact of FD on EC. The asymmetries in this relationship further complicate the analysis. Positive financial shocks (e.g., increased capital inflows) can spur EC by facilitating economic activities (Boufateh & Saadaoui, 2020; Wang & Dong, 2021). By contrast, negative shocks (e.g., financial crises) typically curtail EC by reducing investment and production activities (Boufateh & Saadaoui, 2020; Rehman et al., 2023). This dynamic relationship underscores the necessity of examining FD and EC in light of economic shocks and structural changes to inform policy design better.

Despite a wealth of studies on FD and EC, gaps remain in the understanding of their intricate dynamics, especially in the presence of economic shocks across varying developmental contexts. The existing literature often lacks consensus owing to variations in econometric methods, sample selections, and contextual factors (e.g., Charfeddine & Kahia, 2019; Imran et al., 2023; Ma et al., 2022; Sun et al., 2023; Yu et al., 2022). This study addresses these gaps by exploring the following research questions:

- (1) How does FD influence EC across different levels of economic development?
- (2) What are the asymmetric effects of financial shocks on EC in the short and long term?
- (3) How can policy interventions balance economic growth and environmental sustainability through targeted FD strategies?

Employing the Nonlinear Autoregressive Distributed Lag (NARDL) method by Shin et al. (2014), this study captures the asymmetric effects between explanatory and dependent variables over a 30-year period

from 1990 to 2019, across 173 economies. The analysis covers 56 high-income, 45 upper-middle-income, 50 lower-middle-income, and 22 low-income economies. This study provides comprehensive insights for guiding policy interventions tailored to various economic contexts by addressing these research questions. Hence, the findings of this study provide critical evidence for decision-makers aiming to design financial policies that support sustainable energy transitions without reducing economic stability. The remainder of this paper is organised as follows. Section 2 discusses the theoretical framework, Section 3 reviews the literature and develops the hypotheses, Section 4 details the data and methodology, Section 5 presents the empirical results and discussion, and Section 6 concludes with policy recommendations.

## 2. Theoretical Framework

To provide a tractable theoretical foundation for the empirical specification, consider a representative economy of country  $i$  with an aggregate production technology where energy is an input:

$$Y_t = A(FD_t)K_t^\alpha L_t^\beta EC_t^\gamma, \quad \alpha + \beta + \gamma < 1, \quad (1)$$

where  $Y_t$  is output,  $K_t$  is the capital,  $L_t$  denotes the labour input, and  $EC_t$  is energy use. Financial development ( $FD_t$ ) affects production through total factor productivity (TFP) and/or the efficiency of energy through the use of capital. A parsimonious way to capture this is:

$$A(FD_t) = A_0 \exp(\theta FD_t), \quad (2)$$

where  $\theta$  is potentially positive if finance improves allocative efficiency and facilitates technology diffusion. Hence, incorporating finance and energy into an augmented production-function framework is standard in the energy-growth-finance literature (Shahbaz et al., 2013, 2017). Assume the representative producer minimises cost  $C_t = r_t K_t + w_t L_t + p_t^E EC_t$  subject to producing  $Y_t$ . Under Cobb-Douglas technology, the conditional (cost-minimising) demand for energy is proportional to output and inversely related to productivity

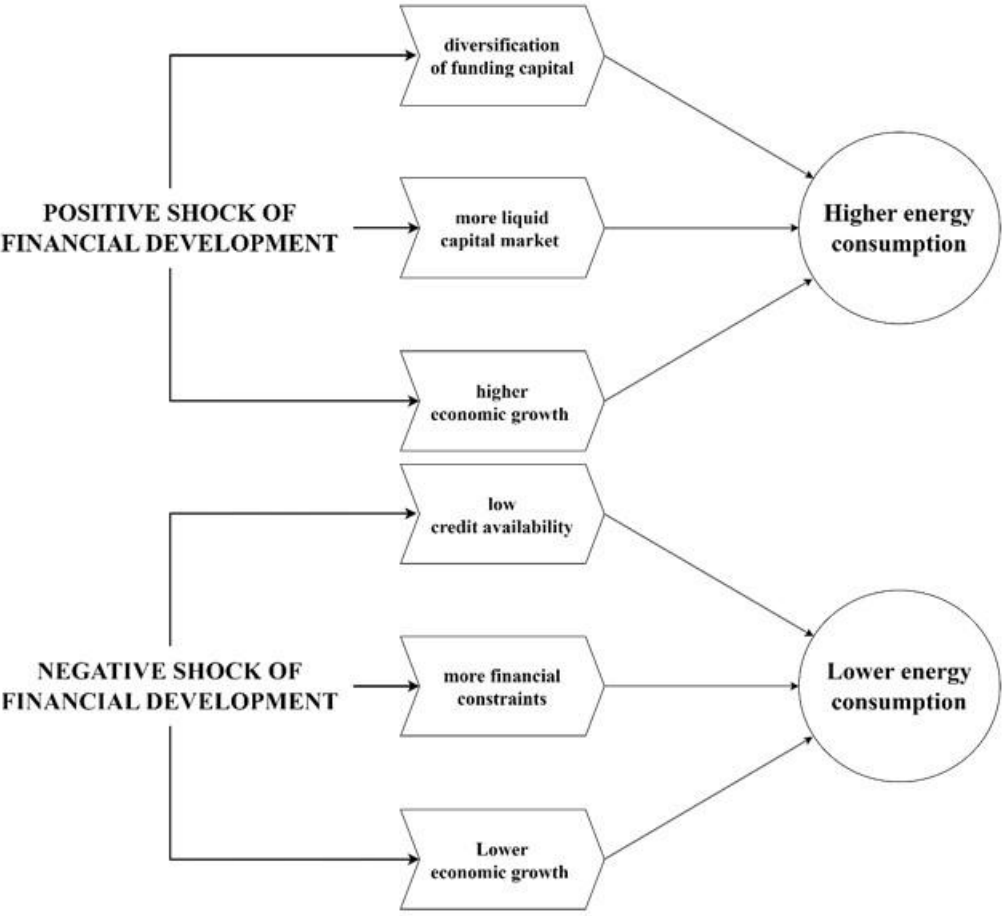
$$EC_t = \gamma \frac{C_t}{p_t^E} \Rightarrow \ln EC_t = \ln Y_t - \ln A(FD_t) + \eta, \quad (3)$$

where  $\eta$  is terms in input prices and elasticities. Substituting  $A(FD_t) = A_0 \exp(\theta FD_t)$ , yields a reduced-form implication:  $\frac{\partial \ln EC_t}{\partial \ln FD_t} = -\theta + \frac{\partial \ln Y_t}{\partial \ln FD_t} + \frac{\partial(\text{relative cost/technology terms})}{\partial \ln FD_t}$ . Hence,  $FD_t$  can increase  $EC_t$  via the scale or expansion component (if finance significantly raises output and energy-using activity), but can decrease  $E_t$  if the finance-induced productivity or efficiency effect dominates. This theoretical mix is consistent with mixed empirical findings in the finance-energy literature.

Indeed, Alshagri et al. (2024) and Sadorsky (2011) identify two primary channels through which FD influences EC. The first channel highlights a positive relationship in which FD promotes EC by fostering economic growth, which, in turn, drives higher energy demand. This relationship is underpinned by three distinct mechanisms: the “direct effect”, the “business effect”, and the “wealth effect”. The “direct effect” arises in advanced financial systems, where consumers can borrow more easily and affordably to purchase

lasting goods, thereby increasing EC. The “business effect” reflects FD’s role in enabling corporations to access financial capital more readily and at lower cost, facilitating business expansion and increased investment activities, thereby heightening energy demand. Lastly, the “wealth effect” pertains to enhanced economic confidence associated with improved FD, which stimulates EC as overall economic activity grows. Meanwhile, the second channel is characterised by the “technological effect,” which suggests that FD can drive the adoption of modern, energy-efficient technologies, thereby reducing EC.

**Figure 2.** The asymmetric effect of FD on EC



(Source: Boufateh & Saadaoui, 2020; Thebuho et al., 2022)

Additionally, the relationship between FD and EC is often asymmetric (see Figure 2), influenced by the differential impacts of positive and negative FD shocks. Positive shocks, which are typically associated with financial openness and foreign capital inflows, enhance the availability of low-cost credit and improve capital market liquidity (Boufateh & Saadaoui, 2020; Wang & Dong, 2021). These dynamics facilitate economic growth, industrial productivity, and increased energy demand by enabling firms and financial institutions to diversify funding sources and secure capital for sustainable energy supply projects (Alshagri et al., 2024; McCloud et al., 2024). Consequently, positive FD shocks tend to augment the EC across industries and households. Conversely, negative FD shocks can suppress EC, which is often linked

to financial crises, such as declining credit growth or nonperforming loans (Meriläinen, 2016; Syed et al., 2022). Economic growth slows during financial crises, reduces consumer spending and corporate investment, and narrows business activities (Shahbaz et al., 2022). Limited credit availability prompts financial institutions to adopt risk-averse strategies to protect shareholder value, constraining financing for innovative or high-risk energy projects (Thebuho et al., 2022). Consequently, firms may face financial limitations, hindering investments in advanced energy production technologies and further reducing EC (Boufateh & Saadaoui, 2020).

### **3. Literature Review and Hypothesis Development**

#### ***3.1. Empirical studies related to financial development and energy consumption***

Numerous empirical studies have explored the complex relationship between FD and EC and have yielded diverse and sometimes contradictory results. Ma and Fu (2020) analysed data from 120 countries between 1991 and 2014 using the generalised method of moments (GMM) approach. Their findings indicated that higher FD is associated with increased EC, particularly in developing countries. This was attributed to the role of FD in alleviating financial constraints, enabling businesses to expand and consumers to purchase goods, all of which drive higher energy demand. In contrast, in developed countries, FD did not significantly impact EC, highlighting the heterogeneity in the influence of FD across income groups. Extending this analysis, Ma et al. (2022) focused on 67 developing countries from 1995 to 2018 and employed a multidimensional approach to measure FD, encompassing the access, depth, and efficiency of financial institutions and markets. Their findings suggest that both financial institutions and markets significantly reduce EC, with financial institutional development (FID) exerting a stronger influence than financial market development (FMD). This distinction reflects the earlier development and dominance of FID in developing economies, where firms rely primarily on indirect financing. They argue that improved financial systems alleviate constraints, enabling higher investment in research and development (R&D) and fostering industrial upgrades. These changes optimise resource allocation, replace low-efficiency industries with technology- and knowledge-intensive sectors, and enhance energy efficiency by reducing EC. Yu et al. (2022) examine the spatial spillover effects of FD on EC between 2005 and 2018. Their analysis revealed contrasting roles for the banking sector and stock market development: while the banking sector promoted EC, stock market development inhibited it. They advocated for increased green credit from banks to support clean energy and emissions reduction, and emphasised the need for balanced growth to mitigate regional inequalities stemming from stock market development.

At the global level, Sun et al. (2023) investigated the impact of FD on renewable EC using panel data from 103 countries spanning 1991 and 2014. They employed the FD index system developed by Svirydzenka (2016) and found that FD positively influences renewable EC, particularly in developed economies. This discrepancy between developed and developing countries underscores the importance of institutional environments, technological capacities, and economic policies. While financial institutions consistently promoted renewable EC, financial markets had no significant global effect, particularly in developing economies with less mature market structures. Additionally, Farhani and Solarin (2017)

explored the long-term relationship between FD and EC in the United States from 1973 to 2014 using the Bayer-Hanke cointegration approach. They conclude that FD reduces EC by incentivising businesses to adopt energy-efficient production methods. Similar findings were reported by Gómez and Rodríguez (2019) in NAFTA countries, where FD, measured as domestic credit to GDP, promoted technological innovation, leading to lower EC. These studies emphasise the role of FD in fostering energy efficiency through innovation.

Empirical research has also highlighted the nonlinear and asymmetric relationship between FD and EC, revealing diverse dynamics across regions and economic contexts. Mahalik et al. (2017) confirm an inverted U-shaped relationship in Saudi Arabia, where initial FD increases EC by allocating financial credit to productive ventures. However, at higher levels, FD fostered energy efficiency through technological adoption. Similarly, Baloch et al. (2019) observed this pattern in OECD countries from 1980 to 2016, finding that advanced FD stages reduce EC by encouraging energy-efficient practices. Gaies et al. (2019) found that while early FD stages increase EC in the MENA region, later stages reduce it by driving renewable energy investment. Wang and Gong (2020) extend these findings to China, showing that provinces with lower FD levels experience increased EC, whereas those with higher FD benefit from energy reduction due to industrial and technological upgrades. Chiu and Lee (2020), analysing 79 countries, demonstrated that banking sector development significantly influences EC, while non-OECD countries experience an inverted U-shaped relationship between financial markets and EC, with financial institutions reducing EC.

Previous studies also emphasise the importance of asymmetric effects and income level distinctions. Qamruzzaman and Jianguo (2020) used the NARDL model to show that both positive and negative FD shocks impact renewable EC differently across 113 countries. Positive shocks consistently promote renewable EC, whereas negative shocks decrease renewable EC in lower- and middle-income countries and increase it in upper-middle-income countries. Thebuho et al. (2022) corroborated these asymmetric effects in sub-Saharan Africa, demonstrating that FD improvements increase EC while reducing it. These findings underscore the role of FD in shaping energy demand through financial accessibility, industrial restructuring, and technological adoption, particularly in regions with various economic and institutional frameworks. These studies illustrate that tailored policies that foster sustainable financial systems are essential for aligning economic growth with energy efficiency and environmental goals.

Although previous studies have explored the relationship between FD and EC, several gaps remain unaddressed. Previous research has yielded mixed results, indicating that the relationship is neither consistently positive nor negative, and may vary by context, including economic development levels and types of financial markets. Many studies focus on limited sample sizes or specific regions, often neglecting broader global perspectives and the asymmetries caused by positive and negative financial shocks. Furthermore, most studies have failed to account for the dynamic nature of this relationship over time or its sensitivity to economic and financial volatility.

### ***3.2. Hypothesis development***

Existing literature has extensively explored the relationship between FD and EC, yet the nature of this relationship, particularly its potential asymmetry, remains underinvestigated. The assumption of symmetric responses in traditional linear models may obscure important heterogeneous effects in economic and financial data. For instance, Wong (2007) demonstrates that conventional mean-variance frameworks can be inadequate in the presence of nonlinear dominance structures. Meanwhile, Ng et al. (2017) extend stochastic dominance analysis via quantile regression. This extension captures nonlinear relationships and asymmetric impacts across distributions, supporting more flexible asymmetric modelling in decision science. Hence, this study addresses these gaps by employing the NARDL method to capture the asymmetric effects of FD on EC, using a comprehensive sample of 173 economies over three decades. The use of the NARDL model is based on the belief that an increase in FD can have a different impact on economic activity compared to a decrease in FD. Indeed, while conventional analyses largely assume symmetric impacts, recent evidence suggests that FD may not uniformly influence EC, particularly when considering positive and negative financial shocks separately (Qamruzzaman & Jianguo, 2020; Thebuho et al., 2022). Hence, this study provides insights into the dual channels through which FD impacts EC across diverse economic contexts. These findings are expected to bridge the theoretical and empirical gaps and offer guidance for policies that balance economic growth and sustainability. Building upon these considerations, the present study proposes the following hypotheses:

H1: Financial development has a significant asymmetric effect on energy consumption in the long run.

H2: Positive shocks to financial development decrease long-run energy consumption, while negative shocks increase it.

H3: The asymmetric impact of financial development on energy consumption differs significantly across high-income, middle-income, and low-income countries.

## **4. Methodology and Data**

### ***4.1. Data***

Table 1 shows descriptions of the variables, codes, and sources based on previous studies. Research data is collected from the Energy Information Administration (EIA), International Monetary Fund (IMF), and World Development Indicators (WDI) databases. This study attempts to maximise the number of observations in the sample, but some countries did not publish continuous annual data from 1990 to 2019. After exclusions, this study employs annual data spanning the period 1990 - 2019 for 173 economies, comprising 56 high-income economies, 45 upper-middle-income economies, 50 lower-middle-income economies, and 22 low-income economies. Since each economy is observed continuously over 30 years, the dataset constitutes a balanced panel. The sample economies are classified into four income groups following the World Bank income classification.

**Table 1.** Description of the variables in the model

Name	Code	Description	Source
Energy Consumption	EC	Natural logarithm of primary energy consumption measured in terawatt-hours	EIA
Financial Development	FD	Financial Development Index (scale ranging 0 - 100)	IMF
Financial Market Development	FMD	Financial Market Index (scale ranging 0 - 100)	IMF
Financial Institution Development	FID	Financial Institution Index (scale ranging 0 - 100)	IMF
Urbanization	URBAN	Urban population (% of total population)	WDI
Economic growth	GDPPC	Natural logarithm of gross domestic product per capita in current dollars	WDI

In Table 1, EC is measured as the natural logarithm of total primary energy consumption in terawatt-hours and is sourced from the EIA. FD is proxied by the IMF's Financial Development Index (scale from 0 to 100), which reflects the overall development of the financial system in terms of depth, access, and efficiency. Similarly, FMD and FID are scaled from 0 to 100, capturing the development of financial markets and financial institutions. URBAN is defined as the percentage of the urban population in the total population and is obtained from the WDI. Lastly, GDPPC is proxied by the natural logarithm of GDP per capita in current US dollars and is also sourced from the WDI. Consistent with the theoretical framework in Section 2, where energy use is linked to the scale of economic activity, urbanisation (URBAN) and economic growth (GDPPC) are included to capture key demographic and scale mechanisms. URBAN proxies structural and demographic shifts that can raise energy demand through higher concentration of industrial, transport, and residential activities (Anwar et al., 2022; Ullah et al., 2022). Meanwhile, GDP per capita captures the scale and affluence channel through which higher economic activity and purchasing power translate into greater energy use (Himawan et al., 2024; Nguyen et al., 2024). Also, businesses tend to expand production, invest more in technology, and build more infrastructure to grow the economy, resulting in high energy demand (Ozcan et al., 2020). Hence, these variables are employed to capture the demographic and economic channels through which financial development influences energy consumption.

#### ***4.2. Methodology***

The NARDL approach adapts the original ARDL model of Pesaran et al. (2001) to account for asymmetric effects in a cointegrated error-correction model, following the framework of Shin et al. (2014). The advantages of this technique for estimating in modelling economic relationships have been documented by Nusair (2016), Salisu and Isah (2017), among others. The NARDL is adaptable to small samples and different forms of non-stationary data, making it a suitable method for empirical studies. Moreover, NARDL separates short- and long-run effects, which is valuable for understanding how an independent variable might have immediate impacts on the dependent variable versus longer-term impacts.

Because the NARDL model is an asymmetric expansion of the linear ARDL, it is useful to present the linear ARDL model first. Pesaran and Shin (1999) and Pesaran et al. (2001) proposed the linear form of the ARDL-bound testing approach, which is a widely used framework to check whether cointegration exists between variables. The approach is as follows.

$$\begin{aligned} \Delta EC_{it} = & \phi_0 + \phi_1 * EC_{it-1} + \phi_2 * FD_{it-1} + \phi_3 * URBAN_{it-1} + \phi_4 * GDPPC_{it-1} \\ & + \delta_1 * \Delta EC_{it-1} + \delta_2 * \Delta FD_{it-1} + \delta_3 * \Delta URBAN_{it-1} + \delta_4 * \Delta GDPPC_{it-1} + \varepsilon_{it}, \end{aligned} \quad (4)$$

where  $\Delta$  is the first difference operator applied to the variable that follows it. The coefficients  $\phi_1, \phi_2, \phi_3, \phi_4$  are the long-run coefficients. The coefficients  $\delta_1, \delta_2, \delta_3, \delta_4$  denote the short-run coefficients.  $\varepsilon_{it}$  is the error term, while  $t$  and  $i$  are country identification and year. According to Table 1, energy consumption (EC) is measured as the logarithm of primary energy consumption, expressed in terawatt-hours. Financial development is captured by the overall financial development index (FD), along with its two subcomponents: financial institutions development (FID) and financial markets development (FMD). A higher value of these indices indicates a more developed financial system. Urbanisation (URBAN) and economic growth (GDPPC) are employed to capture the demographic and economic channels as control variables of the model.

In addition, this study derives the NARDL model by extending the linear ARDL with the partial positive and negative sum decomposition of the exogenous variable FD in which  $FD_{it}^+$  and  $FD_{it}^-$  measure the positive and negative shocks in financial development, respectively as follows:

$$FD_{it}^+ = \sum_{j=1}^t \Delta FD_{ij}^+ = \sum_{j=1}^t \max(\Delta FD_{ij}^+; 0), \quad (5)$$

$$FD_{it}^- = \sum_{j=1}^t \Delta FD_{ij}^- = \sum_{j=1}^t \min(\Delta FD_{ij}^-; 0). \quad (6)$$

This study used three proxies for financial development: overall financial development (FD), financial market development (FMD), and financial institution development (FID). Next, considering the short- and long-run asymmetric effects in the ARDL representation in Equation 4, the NARDL models used for the estimation in this study are as follows:

$$\begin{aligned} \Delta EC_{it} = & \phi_0 + \phi_1 * EC_{it-1} + \phi_2^+ * FD_{it-1}^+ + \phi_2^- * FD_{it-1}^- + \phi_3 * URBAN_{it-1} + \phi_4 * GDPPC_{it-1} \\ & + \delta_1 * \Delta EC_{it-1} + \delta_2^+ * \Delta FD_{it-1}^+ + \delta_2^- * \Delta FD_{it-1}^- + \delta_3 * \Delta URBAN_{it-1} \\ & + \delta_4 * \Delta GDPPC_{it-1} + \varepsilon_{it}. \end{aligned} \quad (7)$$

From Equation 7, the long-term asymmetric response of EC to positive and negative shocks on FD is captured from the coefficients ( $\phi_2^+$  and  $\phi_2^-$ ), while the coefficients estimate the short-term asymmetric response  $\delta_2^+$  and  $\delta_2^-$ . This study performed two steps to confirm the asymmetric effect of FD on EC.

Long-run asymmetry in the relationship between the FD and energy demand was tested in the first step using the Wald test. The presence of long-run asymmetry is confirmed by the rejection of the null hypothesis  $H_0: -\phi_2^+/\phi_1 = -\phi_2^-/\phi_1$ .

Similarly, the second step checks for short-run asymmetry in the relationship between FD and energy demand, which is tested using the Wald test. The rejection of the null hypothesis  $H_0 (\delta_2^+ = \delta_2^-)$  confirms the presence of long-run asymmetry. The results of these two tests can be classified into four cases: (i) The null hypothesis of symmetry is rejected in both the long run and short run, indicating that the impact of financial development (FD) on energy demand is asymmetric in both time frames. (ii) The null hypothesis of symmetry is rejected in the long run but cannot be rejected in the short run, implying long-run asymmetry and short-run symmetry. (iii) The null hypothesis of symmetry cannot be rejected in the long run but is rejected in the short run, suggesting short-run asymmetry and long-run symmetry. (iv) The null hypothesis of symmetry cannot be rejected in either the short or long run, indicating symmetric effects of FD on energy demand. In this case, the NARDL model may be replaced by the traditional ARDL model. Then, the asymmetric error correction of Equation 7 yields the following:  $\delta_2^+ \delta_2^-$

$$\Delta EC_{it} = \phi_0 + \gamma_1 * \Delta EC_{it-1} + \delta_2^+ * \Delta FD_{it-1}^+ + \delta_2^- * \Delta FD_{it-1}^- + \delta_3 * \Delta URBAN_{it-1} + \delta_4 * \Delta GDPPC_{it-1} + \theta * ect_{it-1} + \varepsilon_{it}, \quad (8)$$

where  $ect_{it-1}$  is the asymmetric error correction term and  $\theta$  is the speed of adjustment of the system converging to its long-term equilibrium after a shock.

In econometrics, prior studies may use the ARDL model to evaluate the long-run relationship between variables with different orders of integration, which requires that none of the variables become stationary at the second differencing. In other words, some variables are non-stationary at the level, while others are stationary, for example, an assortment of  $I(0)$  and  $I(1)$  (Shin et al., 2014). Thus, this study applies a unit-root test to determine whether a variable is stationary. However, Sheikh et al. (2020) suggest that cross-sectional dependence in data renders the unit root test no longer reliable. Hence, Pesaran (2007) developed a cross-sectional augmented IPS panel unit root test to address the disadvantages of previous unit root tests. The formula for the cross-sectional augmented IPS unit root test can be expressed as follows:

$$CIPS(N, T) = N^{-1} \sum_{i=1}^N t_i(N, T), \quad (9)$$

whereas the cross-sectional dependence was estimated using Pesaran (2004) CD test.

$$CD = \sqrt{\frac{2T}{N(N-1)}} \left( \sum_{i=1}^{N-1} \sum_{j=i+1}^N p_{ij} \right), \quad (10)$$

where  $N$  is the number of countries in the sample,  $T$  is the number of observations,  $p_{ij}$  is the pairwise correlation between the residuals.

Although unit-root and cointegration diagnostics are standard safeguards, the literature notes that misleading significance can still arise in regressions involving stationary, nearly non-stationary, or mixed-order series (Cheng et al., 2021). Wong and Yue (2024) demonstrated that the t-test in the case where the

model has  $I(0)$  and  $I(1)$  may diverge to infinity, making the conclusion of statistical significance meaningless and without real economic value. Moreover, Wong et al. (2024) stated that stationarity is not an effective tool for detecting spurious regression, because even if both variables are stationary ( $I(0)$ ), the regression may still be spurious if they exhibit strong serial dependence or normal random components. To explicitly address this concern, this study acknowledges the spurious-relationship mechanisms discussed in Cheng et al. (2021), Wong and Yue (2024), as well as the implications highlighted by Wong et al. (2024). Hence, this study not only relies on the panel unit-root evidence but also considers the subsequent cointegration testing step to mitigate these specific risks before interpreting long-run relationships.

In addition, to estimate the NARDL model using panel data, this study applies the PMG and MG estimates adopted by Pesaran et al. (1999). These two estimators suit data characterised by both large  $T$  and  $N$  values and mitigate the endogeneity problem. However, there is a difference between the PMG and MG estimators because of their restrictions on the homogeneity (Thebuho et al., 2022). Following previous research, this study used the Hausman test to determine competence and consistency. If the null hypothesis is rejected, this study can conclude that the MG estimator can be adopted. Otherwise, this study adopts the PMG estimator.

The empirical estimation follows a structured multi-step procedure to ensure the validity of the econometric results. First, cross-sectional dependence among countries is tested to account for potential common shocks and spillover effects. Second, the CIPS panel unit root test is applied to determine the order of integration of each variable and to confirm that all series are integrated of order  $I(0)$  or  $I(1)$ . Third, the existence of long-run cointegration relationships is verified using appropriate bounds testing procedures. Once cointegration is established, the NARDL model is estimated to obtain both long-run asymmetric coefficients and short-run dynamic adjustments. The pooled mean group (PMG) and mean group (MG) estimators are compared, and the Hausman test is employed to select the most appropriate estimator. Subsequently, Wald symmetry tests are conducted to examine the presence of short-run and long-run asymmetries. Finally, a set of post-estimation diagnostic tests is performed to ensure the reliability and robustness of the estimated results.

## 5. Empirical Results and Discussion

**Table 2.** Summary of descriptive statistics

Variable	Mean	Sd	Min	Max
EC	6.6790	1.6281	2.1331	10.1866
FD	29.0336	22.0358	0.3339	100.0000
FMD	19.4599	24.5232	0.0000	100.0000
FID	37.5671	22.0272	0.0000	100.0000
URBAN	54.2721	23.3723	5.4160	100.0000
GDPPC	8.1508	1.5960	3.8972	11.7254

Table 2 presents the descriptive statistics of the model variables. The average value of EC is 6.6790 with a standard deviation of 1.6281, indicating variability in energy usage across observations. The minimum and maximum values are 2.1331 and 10.1866, respectively. The mean FD value was 29.0336 with a broad standard deviation of 22.0358, suggesting significant differences in the FD levels. Reflecting the development level of financial markets, FMD has a mean of 19.4599 and a standard deviation of 24.5232, indicating variability. The average value of FID was 37.5671, with a standard deviation of 22.0272, capturing the development of financial institutions in terms of depth, access, and efficiency. URBAN represents the percentage of the population living in urban areas, with a mean rate of 54.2721% and a standard deviation of 23.3723%. The proxy for economic development, GDPPC, is 8.1508, with a standard deviation of 1.5960, a minimum of 3.8972, and a maximum of 11.7254, reflecting diverse levels of economic prosperity across the sample.

This study uses Pesaran's (2004) cross-sectional dependence test to examine whether the panel time-series data exhibit cross-sectional dependence. Table 3 presents the results of cross-sectional independence tests. The null hypothesis of no cross-sectional dependence for EC, FD, FMD, FID, URBAN, and GDPPC may be rejected. These results indicate that the panel time series data exhibit cross-sectional dependence.

**Table 3.** Cross-sectional dependency test of Pesaran (2004)

Variable	CD-test
EC	104.152***
FD	247.065***
FMD	84.234***
FID	252.387***
URBAN	307.082***
GDPPC	560.529***

Note: \*\*\*, \*\*, and \* denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Next, this study performs a unit root test to avoid spurious regressions in the model. Due to the presence of cross-sectional dependence, this study uses a cross-sectional augmented IPS panel unit root test developed by Pesaran (2007), as presented in Table 4. The results show that some variables are stationary at different levels (I(0) or I(1)), indicating the suitability of the panel NARDL approach for the estimation.

**Table 4.** IPS panel unit root test

Variable	Intercept		Intercept & Trend	
	Level (I(0))	First Difference (I(1))	Level (I(0))	First Difference (I(1))
EC	0.1540	-37.6001***	-10.6003***	
FD	-1.0255	-37.9926***	-10.3643***	
FD <sup>+</sup>	10.2170	-36.0580***	-4.3109***	
FD <sup>-</sup>	9.2581	-36.8740***	-8.4842***	
FMD	-7.6766***		-2.4153***	
FMD <sup>+</sup>	-6.8024***		4.6764	-35.3500***
FMD <sup>-</sup>	20.9558	-31.6753***	-6.0997***	
FID	2.4478	-37.8955***	-10.5781***	
FID <sup>+</sup>	12.3726	-35.9854***	-5.2988***	
FID <sup>-</sup>	5.1449	-36.9678***	-8.5867***	
URBAN	15.7938	-2.9035***	4.7241	-10.0940***
GDPPC	7.7326	-31.1408***	-4.4846***	

Note: FD<sup>+</sup> and FD<sup>-</sup> are the partial sum processes of positive and negative shocks in FD. \*\*\*, \*\*, and \* denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Following the concerns raised in the spurious-relationship literature (Cheng et al., 2021; Wong et al., 2024; Wong & Yue, 2024), this study explicitly verifies that the regression results are not driven by spurious significance. Specifically, this study confirms the integration properties using the CIPS unit-root test (Table 4) and proceeds only after establishing the required cointegration evidence for the long-run relationship. These diagnostics mitigate the risk of false inference highlighted in the above studies and support the validity of the estimated long-run asymmetric effects. In addition, because the NARDL framework is designed to capture asymmetric adjustments, this study performs tests of linear constraints on the estimated coefficients (Wald test), based on the idea of Hui et al. (2017). Specifically, the short-term Wald test ( $W_{SR}$ ) assesses whether the coefficients of short-term change in positive and negative shocks are equal, while the long-term Wald test ( $W_{LR}$ ) assesses whether the long-term effects associated with positive and negative shocks are equal. Rejecting the  $W_{SR}$  (or  $W_{LR}$ ) provides evidence of short-term (long-term) asymmetry, consistent with the nonlinear adjustment mechanism implied by Hui et al. (2017).

Note on Cointegration (Bounds Testing): Prior to NARDL estimation, this study conducted the panel bounds test following Pesaran et al. (2001) to confirm the existence of long-run cointegrating relationships among the variables. The computed F-statistics for all model specifications exceeded the upper critical bound at the 5% significance level, confirming cointegration and validating the subsequent NARDL long-run estimates. These results are available from the author upon request.

Table 5 shows the results of the asymmetric effect of FD on EC using the NARDL. The p-value of the Hausman test was 0.8903, implying that the null hypothesis could not be rejected. This finding supports the PMG estimator as the most efficient and preferred estimator for exploring the asymmetric effect of FD on EC. Through the Wald test for long- and short-run asymmetric effects, this study found that the  $W_{LR}$  rejects the null hypothesis of the long-run asymmetric effect. In contrast,  $W_{SR}$  may accept the null hypothesis of the short-run asymmetric effect. The Durbin-Watson test values range from 2.1961 to 2.2848 (approximately 2), indicating no autocorrelation in the residuals. The Jarque-Bera test shows significant values, but it does not significantly affect the estimated results in the case of a large sample (5,190 observations), according to the Central Limit Theorem (CLT). First, the critical values of the boundary test constructed by Pesaran et al. (2001) are based on the asymptotic assumption. Therefore, the validity of the F-test depends primarily on a sufficiently large sample size ( $T \rightarrow \infty$ ) rather than the absolute normality of the residuals. Second, according to the CLT, for large sample sizes, the sample distribution of OLS estimates will approximate a normal distribution even if the population error is non-normal. Hamilton (1994) and Wooldridge (2012) assert that the t-statistics and F-test remain asymptotically significant in large-sample time-series models, provided the model does not violate the assumption of autocorrelation. Since the model passed the Breusch-Godfrey test for autocorrelation (as shown in Table 5), the effect of non-normal error is negligible on the conclusion about cointegration in the large panel sample (5,190 observations). Regarding post-estimation diagnostics, Durbin-Watson statistics for all full-sample models are close to 2.0. For the upper-middle-income sub-sample, DW values are marginally elevated ( $DW \approx 2.46-2.55$ ); the Wooldridge (2012) serial correlation test confirmed no significant first-

order autocorrelation at the 5% level across all income-group sub-samples, confirming the reliability of sub-group estimates.

**Table 5.** Asymmetric effect of FD on EC

Dependent variable: EC	Long-run	Short-run
FD <sup>+</sup>	-0.0014*** (-3.27)	
FD <sup>-</sup>	0.0046*** (7.89)	
URBAN	0.0016 (1.46)	
GDPPC	0.1334*** (14.04)	
ECT <sub>t-1</sub>		-0.2402*** (-13.68)
Δ FD <sup>+</sup>		0.0043* (1.81)
Δ FD <sup>-</sup>		0.0054* (1.82)
Δ URBAN		0.0746* (1.74)
Δ GDPPC		0.0405* (1.89)
Constant		1.3565*** (12.87)
Hausman test	0.8903	
W <sub>LR</sub>	125.47***	
W <sub>SR</sub>		0.05
Durbin-Watson test	2.2848	2.1961
Jarque-Bera test		222.4765***

Note: All estimations are based on the nonlinear ARDL in Equation 7 and its associated error-correction in Equation 8. FD<sup>+</sup> and FD<sup>-</sup> are the partial sum processes of positive and negative shocks in FD. Δ is the first difference operator applied to the variable that follows it. W<sub>LR</sub> tests the null hypothesis of long-run symmetry ( $H_0: -\phi_2^+/\phi_1 = -\phi_2^-/\phi_1$ ), WSR tests the null hypothesis of short-run symmetry ( $H_0: \delta_2^+ = \delta_2^-$ ). The Hausman test determines whether PMG or MG is more appropriate. Durbin-Watson and Jarque-Bera tests are applied to check autocorrelation and normal distribution in the residuals. ECT<sub>t-1</sub> reflects the error correction term. \*\*\*, \*\*, and \* denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Thus, this study concludes that only the long-run asymmetric effect of FD on EC exists. Moreover, the coefficient of FD<sup>+</sup> is -0.0014 and is statistically significant at the 10% level, indicating that an improvement in FD may inhibit EC. A unit increase in FD shock (FD<sup>+</sup>) results in a negative change of 0.0014 units in energy demand. This finding suggests that FD incentivises the allocation of capital to more efficient technologies, cleaner production processes, and energy-saving investments, rather than to energy-intensive activities, thereby promoting economic growth and improvements in environmental sustainability. Therefore, financial development not only contributes to economic growth but also helps improve environmental sustainability. In contrast, the coefficient of FD<sup>-</sup> is 0.0046, and the statistical significance is at the 10% level, indicating that a unit decrease in FD (FD<sup>-</sup>) leads to an increase of 0.0046 units in EC. This asymmetric response suggests that financial decline may distort firms' and households' energy-use behaviour. In periods of financial crisis, it can force firms to postpone investment in modern and energy-efficient technologies and instead rely on older, less efficient, and more energy-intensive

production methods. As a result, financial contractions may inadvertently raise aggregate energy consumption by locking economic agents into inefficient energy-use patterns.

In addition, the speed of adjustment of the model was approximately 24.02% per year ( $ECT^{t-1} = -0.2402$ ), meaning that deviations from the long-run equilibrium are corrected at this rate annually, further suggesting that deviations from the long-run equilibrium are corrected gradually, highlighting the persistent nature of financial-energy linkages. The coefficients of the positive and negative shocks to FD in the short run are significantly positive at the 10% level, implying that an increase or decrease of one unit in FD may lead to increases of 0.0043 and 0.0054 units in EC in the short run, respectively. The findings are consistent with previous empirical evidence of Baloch et al. (2019), Gaies et al. (2019), Gómez and Rodríguez (2019), Chiu and Lee (2020), Wang and Gong (2020), Thebuho et al. (2022), Sun et al. (2023), and many other works. This finding suggests that both financial expansions and contractions generate short-run adjustments that are energy-intensive. In periods of financial expansion, improved access to credit stimulates production, investment, and consumption activities, thereby raising immediate energy demand. Notably, financial contractions also appear to increase short-run energy consumption, which may reflect firms' reliance on less efficient and more energy-intensive production technologies when facing credit constraints, as well as households' continued use of outdated energy-consuming appliances due to postponed replacement and investment decisions.

Moreover, to explore the impact of the FD dimensions on EC, this study separates FD into two dimensions, FMD and FID, and re-estimates the equation for the asymmetric effect of FD. To justify the use of a nonlinear specification, this study conducts Wald tests for long-run ( $W_{LR}$ ) and short-run ( $W_{SR}$ ) symmetry. The rejection of the null hypothesis of symmetry implies that positive and negative changes in financial development exert statistically different impacts on energy consumption, confirming the presence of asymmetric adjustment (NARDL). This study presents the results in Table 6 and finds that both FMD and FID reject the null hypothesis of the Wald test for long-run asymmetric impact, but may not reject the short-run asymmetric influence. This result indicates that, similar to FD, FMD and FID may only have a long-run asymmetric effect on EC. Similarly, the Durbin-Watson test values are 2.1883 and 2.1965, indicating no autocorrelation in the residuals. Although the Jarque-Bera statistics are statistically significant, this does not undermine the reliability of the estimators, given the large sample size, as consistency and asymptotic normality are preserved. These results collectively confirm the adequacy of the estimated NARDL specifications.

**Table 6.** Asymmetric effect of dimensions of FD (DFD) on EC

Dependent variable: EC	Dimensions of FD: FMD		Dimensions of FD: FID	
	Long-run	Short-run	Long-run	Short-run
DFD <sup>+</sup>	-0.0096*** (-3.48)		-0.0003 (-0.54)	
DFD <sup>-</sup>	0.0032*** (8.53)		0.0079*** (11.18)	
URBAN	0.0009 (0.82)		-0.0021 (-1.55)	
GDPPC	0.1409*** (16.26)		0.1089*** (10.02)	

ECT <sub>t-1</sub>		-0.2477*** (-14.14)		-0.2341*** (-13.27)
Δ DFD <sup>+</sup>		0.0925** (1.60)		0.0032** (2.25)
Δ DFD <sup>-</sup>		-0.0366 (-0.39)		0.0023 (1.33)
Δ URBAN		0.0653 (1.22)		0.0897* (1.74)
Δ GDPPC		0.0398** (1.96)		0.0392* (1.84)
Constant		1.4044*** (12.94)		1.4199*** (12.42)
Hausman test	0.9917		0.8133	
W <sub>LR</sub>	167.55***		133.63***	
W <sub>SR</sub>		0.93		0.13
Durbin-Watson test	2.1913	2.1952	2.1883	2.1965
Jarque-Bera test		230.6989***		221.9530***

Note: All estimations are based on the nonlinear ARDL in Equation 7 and its associated error-correction in Equation 8. DFD<sup>+</sup> and DFD<sup>-</sup> are the partial sum processes of positive and negative shocks in each dimensions of FD. Δ is the first difference operator applied to the variable that follows it. W<sub>LR</sub> tests the null hypothesis of long-run symmetry (H<sub>0</sub>:  $-\phi_2^+/\phi_1 = -\phi_2^-/\phi_1$ ), W<sub>SR</sub> tests the null hypothesis of short-run symmetry (H<sub>0</sub>:  $\delta_2^+ = \delta_2^-$ ). The Hausman test determines whether PMG or MG is more appropriate. Durbin-Watson and Jarque-Bera tests are applied to check autocorrelation and normal distribution in the residuals. ECT<sub>t-1</sub> reflects the error correction term. \*\*\*, \*\*, and \* denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Regarding FMD in Table 6, the coefficient of FMD<sup>+</sup> is -0.0096, and the statistical significance is at the 1% level, indicating that a unit increase in FMD (FMD<sup>+</sup>) leads to a decrease of 0.0096 units in EC. This finding implies that financial market development facilitates investments in energy-efficient and cleaner technologies, thereby reducing energy consumption. Conversely, the coefficient of FMD<sup>-</sup> is 0.0032, and the statistical significance is at the 1% level, showing that a unit decrease in FMD (FMD<sup>-</sup>) leads to an increase of 0.0032 units in EC. This result reflects that financial market contractions force firms to revert to more energy-intensive production methods, resulting in higher energy demand. Additionally, while the coefficient of the negative shock of FID is significant at the 1% level, a positive shock of FID yields an insignificant statistical result. These findings highlight a strong asymmetric structural transformation channel, as assumed in this study. Similar to FD, empirical results for FMD and FID highlight the crucial role of financial markets and financial institutions in driving the economy toward energy consumption reduction. However, the coexistence of these opposing long-run effects provides strong evidence of asymmetric adjustment and highlights the vulnerability of energy efficiency gains to financial market instability.

More importantly, the results in Table 6 also suggest that a positive shock in FID and FMD (FID<sup>+</sup> and FMD<sup>+</sup>) would be followed by an increase in EC in the short term. Specifically, short-run coefficients of Δ FID<sup>+</sup> and Δ FID<sup>-</sup> are 0.0032 and 0.0023, respectively. These results imply that when financial institutions expand, improved access to credit encourages firms to scale up production and households to increase consumption, thereby raising energy demand. Similarly, financial market expansion initially raises energy use through heightened investment and trading activities. Prior studies, including Mahalik et al. (2017), Destek (2017), Gómez and Rodríguez (2019), Chiu and Lee (2020), Ma et al. (2022), Yu et al. (2022), and Sun et al. (2023), found similar findings. The divergence between these short-run effects and the long-

run impacts of FD, FID, and FMD suggests that financial deepening first generates energy-intensive transitional dynamics before inducing structural shifts toward cleaner and more energy-efficient technologies.

Considering that differences in income groups may lead to variations in the asymmetric effect of FD on EC, this study categorises the sample into high-, middle-, and low-income groups. This study then re-estimates the NARDL model with three proxies for FD, FMD, and FID, and presents the results in Tables 7, 8, and 9. In these tables, the Wald test revealed differences in each income group. In particular, high-income countries have an asymmetric impact of positive and negative FD shocks on EC in the long and short run. While high- and lower-middle-income countries only experience an asymmetric impact of positive and negative shocks of FD on EC in the long run, there are no long-term or short-term asymmetric effects in low-income countries.

The heterogeneity results in Tables A1-A3 (shown in the Appendix) reveal asymmetric and income-dependent effects of FD, FMD, and FID on EC. In high-income economies, both positive and negative shocks to FD, FMD, and FID generally increase long-run energy consumption, with negative shocks exerting stronger effects. It indicates that mature financial-industrial systems remain sensitive to financial instability. In upper-middle-income economies, financial market deepening significantly reduces energy consumption, whereas financial contractions increase it, revealing a clear asymmetric structural transformation channel. By contrast, lower-middle-income economies exhibit predominantly energy-increasing effects from both positive and negative financial shocks, suggesting that financial expansion is still largely channelled into energy-intensive production activities. In low-income countries, the long-run effects of FD and FID are mostly insignificant, while negative shocks to FMD significantly increase energy consumption, reflecting weak financial transmission mechanisms and high vulnerability to financial instability.

These heterogeneous patterns suggest that financial development does not yield uniform energy outcomes across countries at different stages of development. For high-income economies, the energy-intensive response to both financial expansion and contraction can be explained by the structural characteristics of their mature financial and industrial systems. Financial expansion in these economies is typically associated with large-scale capital flows into advanced manufacturing, digital infrastructure, real estate, and high-technology sectors, all of which require substantial and continuous energy inputs despite efficiency improvements. Consequently, increases in financial development tend to stimulate investment activities, which in turn raise aggregate energy demand. Conversely, financial contractions often disrupt long-term investment planning and delay the replacement of capital stock with newer, more energy-efficient technologies. These adjustment frictions cause financial downturns to also generate relatively high energy consumption, resulting in an energy-intensive response under both positive and negative financial shocks.

In upper-middle-income countries, the heterogeneous long-run effects of FD components reflect the transitional nature of their financial and industrial structures. Negative shocks in FD increase EC because

financial contractions constrain firms' access to formal credit and delay investment in energy-efficient technologies, thereby locking production into relatively outdated and energy-intensive capital stock. In contrast, both positive and negative shocks to FMD reduce energy use, indicating that capital markets in these economies increasingly channel resources toward efficiency-enhancing and low-carbon investments, while suppressing speculative and energy-intensive activities during contractions. Meanwhile, positive shocks to FID raise EC, as banking-led financial deepening primarily finances traditional manufacturing, construction, and infrastructure projects that remain relatively energy-intensive. This divergence highlights the need to redirect bank credit toward green and energy-efficient sectors to support sustainable energy transitions in upper-middle-income countries. However, the absence of a significant long-run relationship between FD and EC in low-income countries can be attributed to the limited depth and inclusiveness of their financial systems. In these economies, financial markets and institutions remain underdeveloped, and changes in FD are not effectively transmitted into economic activities. Energy use in low-income countries is largely driven by subsistence activities, traditional biomass consumption, and basic infrastructure needs, which are relatively insensitive to fluctuations in the financial system.

## 6. Conclusions

This study examines the asymmetric relationship between FD and EC by using a global panel of 173 economies over the period 1990-2019. The motivation of this research stems from the growing role of financial systems in shaping energy demand and the limitations of conventional linear models in capturing nonlinear and asymmetric economic dynamics. Given the increasing emphasis on sustainable development and energy efficiency, understanding how financial expansions and contractions differently influence energy consumption is essential for both academics and policy-makers.

Our empirical results confirm that FD exerts a significant asymmetric effect on EC in the long run, while the short-run effects remain largely symmetric. On the other hand, positive shocks to FD reduce long-run EC by improving access to financial resources, facilitating technological transitions, encouraging sustainable production practices, and promoting energy-efficient investments. In contrast, negative FD shocks increase the long-run EC by constraining credit availability, discouraging investments in energy-efficient technologies, increasing dependence on fossil fuels, and delaying technological progress. It is important to note, however, that H2 holds at the global aggregate level but is not uniform across income groups. In particular, in high-income countries, positive FD shocks are also associated with increases in long-run EC ( $FD^+ = 0.0029$ ), indicating that mature financial and industrial systems can generate energy-intensive effects even under financial expansion. This heterogeneity underscores the importance of income-group-specific policy design rather than uniform financial-energy frameworks. Furthermore, the analysis reveals that both FMD and FID display asymmetric effects on EC. Positive shocks in both components contribute to lower energy consumption in the long run, highlighting the role of well-functioning financial systems in supporting sustainable economic growth. The findings also demonstrate substantial heterogeneity across income groups, indicating that the FD-EC relationship differs significantly between high-, middle-, and low-income economies.

These findings provide valuable insights for decision sciences and practitioners by clarifying how financial system dynamics influence long-term energy consumption outcomes under different economic conditions. By explicitly distinguishing between positive and negative financial development shocks, the results support more informed decision-making in the design of financial and energy policies. Policymakers and practitioners can use these insights to anticipate the energy-related consequences of financial expansions or contractions and to align financial development strategies with sustainability objectives. Moreover, the documented heterogeneity across income groups highlights the importance of context-specific decision frameworks rather than uniform policy approaches, enabling decision-makers to design financial interventions that better balance economic growth with energy efficiency.

This study makes a notable contribution to the theoretical and empirical literature by confirming the asymmetric relationship between FD and EC. The heterogeneous and asymmetrical effect of FD across income groups suggests that a unified financial policy cannot be designed to deliver sustainable energy outcomes. In high-income economies, where both financial expansions and contractions raise long-run EC, policymakers should accompany further financial deepening with stringent green finance regulations. For example, carbon pricing mechanisms and mandatory climate-related disclosure are needed to prevent mature financial systems from reinforcing energy-intensive growth. In high- and middle-income countries, FMD plays a key role in reducing energy use, whereas bank-led FD increases it; therefore, policy efforts should prioritise green capital markets while redirecting bank credit toward renewable energy and energy-efficient sectors. For low- and middle-income economies, where financial expansion remains closely tied to energy-intensive growth and financial contractions sharply worsen energy outcomes, strengthening financial inclusion, expanding concessional green financing, and implementing countercyclical credit support are essential to mitigate the energy-intensive transitional effects and protect energy efficiency gains.

Despite its contributions, this study has several limitations. First, the analysis is based on data covering the period 1990-2019 and may not fully capture recent financial and energy-related disruptions, particularly those that have arisen since the COVID-19 pandemic. Second, the use of composite indices for FD, FMD, and FID may not encompass all dimensions of financial development. Third, data limitations restrict the inclusion of additional factors such as fiscal policy, credit policy, and regional financial stability. Future research could address these limitations by incorporating more recent data, exploring alternative measures of financial development, and examining the role of economic cycles, regional characteristics, and political factors in shaping the asymmetric relationship between financial development and energy consumption.

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## Appendix

**Table A1.** Heterogeneity test results related to the asymmetric effect of FD on EC

Dependent variable: EC	High income		Upper-middle income		Lower-middle income		Low income	
	Long-run	Short-run	Long-run	Short-run	Long-run	Short-run	Long-run	Short-run
FD <sup>+</sup>	0.0029*** (8.36)		-0.0023 (-1.53)		0.0124*** (7.98)		-0.0089 (-0.28)	
FD <sup>-</sup>	0.0046*** (7.42)		0.0029** (1.98)		0.0085*** (5.25)		0.033 (0.92)	
URBAN	-0.0171*** (-15.20)		0.0071*** (2.73)		0.0132*** (4.83)		0.1041 (1.02)	
GDPPC	-0.0134 (-1.18)		0.1182*** (6.47)		0.1454*** (5.22)		0.0764 (0.51)	
ECT <sub>t-1</sub>		-0.2798*** (-10.01)		-0.2798*** (-10.01)		-0.2519*** (-6.95)		-0.5851*** (-9.96)
Δ FD <sup>+</sup>		-0.0023 (-1.52)		0.0089 (1.39)		0.0031 (0.74)		-0.0032 (-0.22)
Δ FD <sup>-</sup>		0.0037 (1.27)		0.0063 (1.25)		0.0024 (0.37)		-0.0092 (-0.53)
Δ URBAN		0.0267 (0.71)		0.0754 (1.07)		0.0750 (0.69)		0.9458 (0.90)
Δ GDPPC		0.0968*** (3.54)		-0.0112 (-0.23)		0.0678 (1.54)		0.0294 (0.49)
Constant		2.6882*** (9.90)		1.5718*** (7.63)		1.0459*** (6.35)		1.1747*** (3.97)
Hausman test	0.7852		0.9001		0.9488		0.0948	
W <sub>LR</sub>	14.96***		28.36***		6.44**		0.73	
W <sub>SR</sub>		2.73*		0.07		0.01		0.05
Durbin-Watson test	2.1767	2.2019	2.4607	2.5531	2.0402	1.9241	1.9194	1.8967
Jarque-Bera test	8.9045**		19.4397***		78.975***		20.721***	

Note: All estimations are based on the nonlinear ARDL in Equation 7 and its associated error-correction in Equation 8. FD<sup>+</sup> and FD<sup>-</sup> are the partial sum processes of positive and negative shocks in FD. Δ is the first difference operator applied to the variable that follows it. W<sub>LR</sub> tests the null hypothesis of long-run symmetry (H<sub>0</sub>:  $-\phi_2^+/\phi_1 = -\phi_2^-/\phi_1$ ), WSR tests the null hypothesis of short-run symmetry (H<sub>0</sub>:  $\delta_2^+ = \delta_2^-$ ). The Hausman test determines whether PMG or MG is more appropriate. Durbin-Watson and Jarque-Bera tests are applied to check autocorrelation and normal distribution in the residuals. ECT<sub>t-1</sub> reflects the error correction term. \*\*\*, \*\*, and \* denote statistical significance at the 1%, 5%, and 10% levels, respectively.

**Table A2.** Heterogeneity test results related to the asymmetric effect of FMD on EC

Dependent variable: EC	High income		Upper-middle income		Lower-middle income		Low income	
	Long-run	Short-run	Long-run	Short-run	Long-run	Short-run	Long-run	Short-run
FMD <sup>+</sup>	0.0021*** (8.45)		-0.0124*** (-11.08)		0.0079*** (8.03)		0.0324 (0.94)	
FMD <sup>-</sup>	0.0037*** (8.04)		-0.0094*** (-4.72)		0.0059*** (4.64)		-0.1688*** (-3.90)	
URBAN	-0.0168*** (-9.21)		0.0078*** (3.22)		0.0223*** (8.61)		0.0273*** (4.53)	
GDPPC	-0.0054 (-0.49)		0.1213*** (6.65)		0.1778*** (6.81)		-0.0642** (-2.07)	
ECT <sub>t-1</sub>		-0.2699*** (-10.49)		-0.2665*** (-6.81)		-0.2547*** (-7.34)		-0.2529*** (-5.03)
Δ FD <sup>+</sup>		0.0055 (0.81)		0.1821 (1.05)		-0.0487 (-0.67)		0.4523** (2.18)
Δ FD <sup>-</sup>		0.0085 (1.15)		-0.2034 (-1.30)		0.1794 (0.68)		-0.1665 (-1.50)
Δ URBAN		0.0225 (0.61)		0.0042 (0.06)		0.1130 (0.61)		-0.3674 (-1.55)
Δ GDPPC		0.0948*** (4.16)		0.0093 (0.20)		0.0568 (1.23)		0.0324 (0.71)
Constant		2.5764*** (10.23)		1.5171*** (6.66)		0.9121*** (5.68)		1.0223*** (5.10)
Hausman test	0.6159		0.4269		0.6977		0.4374	
W <sub>LR</sub>	26.63***		2.64		6.11**		26.91***	
W <sub>SR</sub>		0.07		1.50		0.57		4.47**
Durbin-Watson test	2.1811	2.2013	2.4619	2.5527	2.0384	1.9270	1.9229	1.8918
Jarque-Bera test	9.438***		6.241**		1626.051***		85.337***	

Note: All estimations are based on the nonlinear ARDL in Equation 7 and its associated error-correction in Equation 8. FD<sup>+</sup> and FD<sup>-</sup> are the partial sum processes of positive and negative shocks in FD. Δ is the first difference operator applied to the variable that follows it. W<sub>LR</sub> tests the null hypothesis of long-run symmetry (H<sub>0</sub>:  $-\phi_2^+/\phi_1 = -\phi_2^-/\phi_1$ ), W<sub>SR</sub> tests the null hypothesis of short-run symmetry (H<sub>0</sub>:  $\delta_2^+ = \delta_2^-$ ). The Hausman test determines whether PMG or MG is more appropriate. Durbin-Watson and Jarque-Bera tests are applied to check autocorrelation and normal distribution in the residuals. ECT<sub>t-1</sub> reflects the error correction term. \*\*\*, \*\*, and \* denote statistical significance at the 1%, 5%, and 10% levels, respectively.

**Table A3.** Heterogeneity test results related to the asymmetric effect of FID on EC

Dependent variable: EC	High income		Upper-middle income		Lower-middle income		Low income	
	Long-run	Short-run	Long-run	Short-run	Long-run	Short-run	Long-run	Short-run
FID <sup>+</sup>	0.0029*** (5.66)		0.0137** (2.40)		0.0033** (2.09)		0.0007 (0.05)	
FID <sup>-</sup>	0.0055*** (7.39)		0.0216 (0.81)		-0.0004 (-0.14)		0.0198 (1.01)	
URBAN	-0.0153*** (-11.91)		-0.0482 (-1.48)		0.0270*** (7.98)		0.0742 (0.74)	
GDPPC	0.0139 (0.90)		0.0944 (1.01)		0.0177 (0.64)		0.0953 (0.59)	
ECT <sub>t-1</sub>		-0.2769*** (-9.17)		-0.6199*** (-15.31)		-0.2510*** (-6.77)		-0.5943*** (-10.07)
ΔFD <sup>+</sup>		-0.0001 (-0.36)		0.0008 (0.31)		0.0042 (1.56)		-0.0024 (-0.34)
ΔFD <sup>-</sup>		0.0001 (0.09)		0.0041 (1.27)		0.0033 (0.82)		-0.0054 (-0.59)
ΔURBAN		-0.0168 (-0.50)		-0.0518 (-0.33)		0.0714 (0.71)		1.4135 (1.10)
ΔGDPPC		0.0928*** (3.88)		-0.0189 (-0.43)		0.0943** (2.12)		0.0097 (0.19)
Constant		2.5445*** (9.16)		5.0923*** (4.75)		1.1438*** (6.13)		1.7841* (1.79)
Hausman test	0.8630		0.0000		0.9822		0.0727	
W <sub>LR</sub>	13.61***		0.08		1.50		0.59	
W <sub>SR</sub>		0.06		0.54		0.02		0.05
Durbin-Watson test	2.1657	2.1973	2.4615	2.5676	2.0358	1.9423	1.9191	1.8976
Jarque-Bera test	11.2123***		33.3687***		177.5382***		4.8378*	

Note: All estimations are based on the nonlinear ARDL in Equation 7 and its associated error-correction in Equation 8. FD<sup>+</sup> and FD<sup>-</sup> are the partial sum processes of positive and negative shocks in FD. Δ is the first difference operator applied to the variable that follows it. W<sub>LR</sub> tests the null hypothesis of long-run symmetry (H<sub>0</sub>:  $-\phi_2^+/\phi_1 = -\phi_2^-/\phi_1$ ), W<sub>SR</sub> tests the null hypothesis of short-run symmetry (H<sub>0</sub>:  $\delta_2^+ = \delta_2^-$ ). The Hausman test determines whether PMG or MG is more appropriate. Durbin-Watson and Jarque-Bera tests are applied to check autocorrelation and normal distribution in the residuals. ECT<sub>t-1</sub> reflects the error correction term. \*\*\*, \*\*, and \* denote statistical significance at the 1%, 5%, and 10% levels, respectively.