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*Research article*

## **Club convergence in energy diversification among low- and lower-middle-income countries: The role of domestic credit and income**

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**Abstract:** This study examined the long-run dynamics of energy diversification in 46 low- and lower-middle-income countries, with particular emphasis on the roles of domestic credit and income levels. Applying the Phillips–Sul convergence framework to energy concentration as an inverse measure of diversification, we found no evidence of full-sample convergence despite overall diversification gains and reduced cross-country dispersion. Instead, countries form three distinct convergence clubs, differentiated by their initial energy diversification levels and subsequent trajectories. Economies with more diversified starting points continue to broaden their energy mix, while those with highly concentrated systems exhibit slower and more limited diversification. Further regression analysis showed that higher levels of domestic credit are consistently associated with greater energy diversification. The relationship between income and diversification is nonlinear: diversification initially increases with gross domestic product (GDP) per capita but declines beyond an estimated turning point of approximately PPP\$2203, with most observations lying below this threshold. Importantly, interaction results reveal that the diversification effect of domestic credit is income-dependent, with credit expansion exerting a stronger impact at lower income levels. Overall, the findings suggest that effective energy diversification requires a staged and context-sensitive approach, in which financial policies evolve alongside income levels and existing energy structures. Aligning financial conditions with realistic energy transition pathways is likely to be central to achieving sustained diversification outcomes in developing economies.

**Keywords:** energy diversification; club convergence; domestic credit; income levels; low- and lower-middle-income countries

**JEL Codes:** O47, Q01, Q42

## 1. Introduction

Achieving a diversified energy system is increasingly recognized as a cornerstone of sustainable development, energy security, and macroeconomic resilience (Solarin et al., 2024). Heavy reliance on a narrow set of energy sources—such as coal, oil, and natural gas—exposes economies to external price volatility, supply disruptions, and climate-related risks, while also constraining long-run structural transformation (Baz et al., 2021). Energy diversification, which reflects how balanced the energy mix is across multiple sources, therefore provides a broader and more informative measure of energy system resilience than renewable energy expansion alone, as it captures reductions in concentration risk across the overall energy system.

These challenges are particularly pronounced in low- and lower-middle-income countries (L/LMICs). Rapid growth in energy demand driven by population growth, urbanization, and industrialization places increasing pressure on existing infrastructure, while underdeveloped financial systems, severe financing constraints, and low income levels limit the scale and direction of energy investment (Achuo et al., 2024; Iqbal and Noor, 2023). As a result, L/LMICs are more vulnerable to energy shocks and face greater difficulty in financing a transition toward more diversified and resilient energy systems. Understanding how energy diversification evolves over time in these countries is therefore of critical importance.

The concept of energy diversification convergence moves beyond static cross-country comparisons and focuses on whether countries with initially different energy structures tend to converge toward similar diversification levels over time (Bernard and Durlauf, 1995). Evidence of convergence would suggest gradual catch-up driven by mechanisms such as technology diffusion, institutional adaptation, improved access to finance, and rising income levels. By contrast, persistent divergence would point to enduring structural constraints—including differences in per-capita income, financial capacity, and policy environments—leading to heterogeneous transition paths and multiple long-run equilibria in energy diversification (Phillips and Sul, 2007, 2009).

Domestic financial systems—particularly, the domestic credit provision to the private sector—play a central role in enabling energy diversification. Investments in alternative energy sources typically involve high upfront costs, long payback periods, and substantial risk, making access to finance a critical prerequisite (Calcaterra et al., 2024). However, the effectiveness of domestic credit in supporting diversification is unlikely to be uniform across countries. In many L/LMICs, underdeveloped financial systems and risk-averse banking sectors tend to allocate credit toward established and lower-risk fossil-fuel activities, rather than toward capital-intensive energy diversification projects with long payback periods (Ma and Mao, 2025; Saadaoui and Chtourou, 2023).

Economic development is another important factor shaping energy diversification. The relationship between energy use and economic development has long been examined within the energy-growth nexus, while the links among energy, income, and environmental outcomes have been studied within the

energy-environment nexus (Hajko et al., 2018; Ozturk, 2010; Pablo-Romero et al., 2024; Tiba and Omri, 2017). Traditionally, studies in these research areas have focused primarily on aggregate energy consumption, renewable energy, or environmental outcomes. More recently, several studies, including Triguero-Ruiz et al. (2025), Shahbaz et al. (2023), Ağazade (2026), and Kuziboev et al. (2025), have extended these research streams by examining the concentration and diversification of the energy mix as a structural energy characteristic. However, relatively little attention has been paid to how income and financial development jointly shape energy diversification, particularly in L/LMICs.

Within this broader literature, rising per-capita income is associated with greater fiscal and investment capacity, higher capital formation, and increased spending on infrastructure and innovation, which together enhance countries' abilities to finance diversified and capital-intensive energy investments (Pata et al., 2023; Zafar et al., 2019). Consequently, the impact of domestic credit on energy diversification may be income-dependent, as differences in economic development are likely to influence how effectively domestic credit supports investment in energy diversification. Investigating this income heterogeneity is crucial for understanding whether financial development can foster convergence in energy diversification among L/LMICs or instead contribute to persistent divergence.

Existing studies consistently show that domestic credit and per-capita income matter for renewable energy deployment and energy diversification, but their effects are highly heterogeneous and context-specific rather than uniform. In particular, several studies found that domestic credit does not consistently promote renewable energy or diversification, and can be weak, insignificant, or even negative in lower-income or financially underdeveloped economies, where credit tends to support incumbent or lower-risk energy activities instead of structural change (Diallo and Ouoba, 2024; Kuziboev et al., 2025; Le et al., 2020). Similarly, per-capita GDP is found to exert nonlinear or regime-dependent effects, with income growth initially reinforcing energy concentration before facilitating diversification only at higher development stages (Le et al., 2020; Nawaz and Rahman, 2023; Nguyen et al., 2025). Importantly, these findings imply that the effectiveness of domestic credit is likely conditioned by income level, yet most studies examine finance and income separately, rather than testing whether credit effects depend on economic income (Kuziboev et al., 2025; Vatamanu and Zugravu, 2023). Moreover, the bulk of the literature focuses on particular aspects of the energy transition, such as fossil-fuel dependence in the energy mix, renewable-energy development, or consumption levels (Cheng and Jiang, 2024; Eren et al., 2019; Li et al., 2021; Saadaoui and Chtourou, 2023), while energy diversification as a system-wide outcome remains relatively underexplored. Finally, although convergence and club-convergence methods have been applied to energy-related indicators in selected contexts, existing evidence offers limited insight into whether L/LMICs converge toward common or multiple long-run energy diversification paths, and how domestic credit and income jointly shape those dynamics (Eren et al., 2019; Nguyen et al., 2025).

Motivated by these gaps, this study addresses the following research questions:

1. *Do energy diversification levels among L/LMICs converge to a common long-run equilibrium, or do they converge toward different steady-state levels?*
2. *What roles do domestic credit and economic income play in shaping the convergence dynamics of energy diversification?*
3. *Is the impact of domestic credit on energy diversification dependent on income levels?*

Energy diversification can be examined from either the production or the consumption perspective. Energy production diversification reflects the diversity of energy sources produced within an economy, whereas energy consumption diversification reflects the diversity of energy sources

consumed. This study focuses on energy consumption diversification. Accordingly, energy diversification is primarily measured as the concentration of primary energy consumption across five energy sources: (i) coal, (ii) natural gas, (iii) petroleum and other liquids, (iv) nuclear energy, and (v) renewable energy.

This paper makes four main contributions. First, it extends the energy convergence literature by focusing explicitly on energy diversification, a dimension closely linked to energy security and transition resilience. Second, it provides L/LMICs-specific evidence, highlighting heterogeneity within developing economies rather than treating them as a homogeneous group. Third, it integrates domestic credit and income interactions into the convergence framework, offering new insights into the income-dependent role of finance in energy diversification. Finally, by combining convergence analysis with panel econometric techniques, the study bridges macro-level transition dynamics with country-level financial and economic conditions.

The remainder of the paper is organized as follows. Section 2 reviews the related literature and develops the hypotheses. Section 3 presents the data and methodology. Section 4 reports and discusses the empirical results. Section 5 concludes and outlines policy implications for energy and financial development in LLMICs.

## 2. Literature review

### 2.1. Convergence in energy diversification

The convergence literature provides several complementary approaches to assess whether economies move toward similar long-run outcomes.  $\beta$ -convergence examines whether initially lagging economies grow faster than more advanced ones, reflecting a catch-up process (Baumol, 1986).  $\sigma$ -convergence, in contrast, focuses on whether cross-sectional dispersion declines over time (Barro and Sala-i-Martin, 1992). Stochastic convergence holds when shocks to the gap between a country and a benchmark are temporary, implying stationarity in relative series, which relies on unit root tests implemented in univariate or panel settings (Bernard and Durlauf, 1996).

Despite their usefulness,  $\beta$ -,  $\sigma$ -, and stochastic convergence approaches typically assume that all economies converge toward a single common steady state. This assumption may be restrictive when countries differ substantially in income levels, financial constraints, policy regimes, and technological capacity. To relax this constraint, Phillips and Sul (2007, 2009) proposed a club convergence framework that allows for heterogeneous transition paths and identified convergence clubs rather than overall convergence. This approach is particularly well-suited to energy systems, where countries may share broad trends while converging toward distinct long-run equilibria.

Convergence methods have been increasingly applied to energy systems, with evidence consistently showing that energy-related variables rarely converge toward a single overall steady state. Instead, convergence typically occurs within distinct groups of countries, reflecting persistent structural, institutional, and technological differences. For example, Tzeremes (2024) finds that per-capita energy consumption across U.S. states forms multiple convergence clubs rather than exhibiting overall convergence. Similar club-based patterns are reported for renewable energy consumption across global samples (Saba and Ngepah, 2022a), U.S. states (Payne et al., 2024), and EU economies (Presno and Landajo, 2021; Saba and Ngepah, 2022b). Pinar (2024) further documents club convergence in

renewable energy innovation, distinguishing innovation-leading economies from those with persistently weaker performance.

Within this broader literature, a smaller but growing strand focuses explicitly on energy diversification, typically using concentration measures such as the Herfindahl-Hirschman Index (HHI), highlighting its role in reducing dependence on dominant fuels and strengthening energy security (Ağazade, 2026; Gozgor and Paramati, 2022). While some studies find evidence of convergence in energy diversification using  $\beta$ -convergence or unit-root approaches (Ağazade, 2026; Solarin et al., 2024), these results weaken once heterogeneity is taken into account. Allowing for differing transition paths reveals distinct convergence clubs rather than overall convergence, particularly among OECD economies (Nguyen et al., 2025). Overall, the evidence suggests that declining dispersion does not imply global convergence, with diversification paths shaped by persistent structural and institutional differences.

Despite growing interest in energy diversification, existing studies largely focus on Organisation for Economic Co-operation and Development (OECD) economies, the European Union, the United States, or broad global samples, leaving L/LMICs relatively underexplored. This gap matters because energy systems in many L/LMICs remain highly concentrated around fossil fuels<sup>1</sup>, heightening exposure to price volatility, import dependence, and supply disruptions. At the same time, pronounced structural heterogeneity—stemming from energy poverty, weak infrastructure, limited access to finance, and institutional constraints—suggests that countries face uneven adjustment paths (Babayomi et al., 2022; Olaniyi et al., 2025). These conditions make convergence toward a single diversification trajectory unlikely and instead point to the emergence of distinct long-run energy outcomes among structurally similar economies. Accordingly, we propose:

*H1: There is no overall convergence in energy diversification among L/LMICs. Instead, these countries form multiple convergence clubs in energy diversification.*

## 2.2. Impacts

### 2.2.1. The impact of domestic credit on energy diversification

Financial development theory highlights that deeper financial systems expand domestic credit, ease liquidity constraints, and improve capital allocation, thereby supporting investment in capital-intensive activities (Beck et al., 2000; Levine, 1997, 2005). These mechanisms are particularly relevant for energy diversification, which requires substantial upfront investment in generation capacity, electricity networks, and system integration (Calcaterra et al., 2024). When access to finance is limited, such investments are often postponed, leaving energy systems heavily reliant on incumbent fossil-fuel technologies. Improved access to domestic credit can ease these constraints by mobilizing capital for non-fossil generation, grid expansion, and storage infrastructure, enabling a broader range of energy sources to enter the system. In doing so, stronger credit provision can reduce energy concentration and enhance system resilience, especially in economies where diversification is constrained by underdeveloped financial markets.

Empirically, a growing literature examines the role of domestic credit and financial development in shaping renewable energy consumption, generally finding a positive association between credit

<sup>1</sup> <https://www.iea.org/reports/electricity-2024>.

availability and renewable deployment (Diallo and Ouoba, 2024; Nawaz and Rahman, 2023; Vatamanu and Zugravu, 2023). While renewable expansion does not fully capture energy diversification, the entry of additional energy sources typically contributes to a more balanced energy mix and lower concentration (Liu et al., 2023). Domestic credit also supports diversification indirectly by enabling technological upgrading and energy-efficiency improvements, allowing firms to invest in cleaner production processes and modern equipment (Ahmad and Uddin, 2025; Habiba et al., 2022). In addition, credit market development facilitates system-level investments—such as grids, storage, and market integration—that are essential for integrating multiple energy sources and sustaining diversification, particularly in developing economies (Calcaterra et al., 2024; Polzin et al., 2019; Raifu et al., 2021).

At the same time, domestic credit expansion does not automatically promote energy diversification. In many developing economies, banks tend to allocate credit toward established, lower-risk sectors that are closely linked to fossil-fuel industries. This lending bias can reinforce carbon lock-in, as existing infrastructure, regulatory frameworks, and contractual arrangements constrain the adoption of alternative energy sources (Seto et al., 2016; Unruh, 2000). Lock-in effects are often strengthened when fossil-fuel projects benefit from subsidies, state guarantees, or long-term contracts that reduce investment risk relative to renewable alternatives, thereby sustaining financing for incumbent carbon-intensive assets (Campiglio, 2016). Reflecting these conditions, some studies report weak or negative associations between domestic credit and renewable energy consumption in contexts where financial systems continue to favor conventional energy sectors and green-finance frameworks remain underdeveloped (Ma and Mao, 2025; Saadaoui and Chtourou, 2023).

Despite this growing finance-energy literature, direct evidence on the impact of domestic credit on energy diversification, rather than on renewable energy or emissions alone, remains limited. Existing studies that employ diversification measures—typically, concentration indices such as the Energy HHI—are largely confined to the OECD or selected regional samples (Limi, 2020; Nguyen et al., 2025; Shahbaz et al., 2023). As a result, the role of domestic credit in shaping diversification paths under the financing constraints and structural conditions characteristic of L/LMICs remains underexplored.

Against this background, we argue that the net effect of domestic credit on energy diversification in L/LMICs is likely to be positive. These economies typically face binding financial constraints that limit investment in alternative generation technologies, grid expansion, and system integration. Expanding domestic credit can relax these constraints and enable entry into new energy sources or increased investment into renewable sources, particularly given the highly concentrated, fossil-fuel-based starting point of many L/LMICs energy systems. While misallocation risks and lock-in effects remain relevant, the marginal impact of improved access to finance in easing key bottlenecks is expected to dominate in these contexts.

Accordingly, we propose:

*H2: An increase in domestic credit provided by the financial system leads to greater energy diversification in L/LMICs.*

### 2.2.2. The impact of economic wealth on energy diversification

From a development perspective, rising income generally expands investment capacity, improves infrastructure, and supports structural transformation, all of which can facilitate energy diversification (Ranis and Fei, 1961). Higher income, together with greater capital formation and R&D spending, can promote investment in renewable energy and related infrastructure (Pata et al., 2023; Zafar et al., 2019),

while growing energy demand and the need for uninterrupted energy supply may further encourage a broader energy mix (Gyimah et al., 2022).

Behavioral explanations offer mixed implications. The energy ladder hypothesis suggests that rising income initially promotes diversification but may later lead to re-concentration as a dominant modern fuel emerges (Hosier and Dowd, 1987), whereas the multiple-fuel-use hypothesis emphasizes fuel stacking and more persistent diversification (Masera et al., 2000). At the same time, economic growth can reinforce existing energy structures through scale effects, path dependence, and carbon lock-in, particularly where fossil fuels remain the least-cost option (Seto et al., 2016; Unruh, 2000). Political-economy dynamics may further entrench incumbent technologies, limiting diversification despite continued income growth (Afonso et al., 2020).

Recent studies have extended the broader energy-growth and energy-environment nexuses by examining energy diversification, rather than aggregate energy consumption or renewable energy alone, as a structural feature of the energy mix. However, findings on the role of income in shaping energy diversification remain mixed. Triguero-Ruiz et al. (2025) reported that higher per-capita income and lower pollution intensity are associated with greater energy diversification in OECD countries. In contrast, Kuziboev et al. (2025) found that economic development negatively influences energy diversification across developed economies, while Shahbaz et al. (2023) reported comparable evidence for Australia. Overall, these studies suggest that income plays an important role in shaping energy diversification, although the direction and magnitude of the relationship vary across countries and stages of development. In addition, recent cross-country evidence suggests that countries follow heterogeneous convergence paths in energy diversification across different income groups, reinforcing the importance of examining L/LMICs separately (Ağazade, 2026). Taken together, these studies indicate that evidence on the role of income in shaping energy diversification in L/LMICs remains limited, highlighting the need for further investigation.

Higher income is often associated with greater investment capacity, infrastructure development, and technological adoption, which can support renewable energy expansion and diversification, though these effects are neither automatic nor uniform across countries (Eren et al., 2019; Murshed and Tanha, 2021; Saadaoui and Chtourou, 2023). At low income levels, however, economic growth tends to raise energy demand that is met primarily through existing fossil-fuel sources, increasing concentration. Only at higher income levels does GDP per capita begin to facilitate diversification (Kuziboev et al., 2025; Nguyen et al., 2025).

The relatively less mature energy systems in L/LMICs suggest that rising income may ease financing and infrastructure constraints, allowing new energy sources to be added without displacing large legacy assets. Accordingly, we propose:

*H3: Higher GDP per capita is associated with greater energy diversification in L/LMICs.*

### 2.2.3. The income effects on the domestic credit-energy diversification link

The effect of domestic credit on energy diversification is likely to depend on a country's level of economic development, as financial depth, credit allocation, and the feasibility of financing capital-intensive energy projects vary markedly across income groups. Existing evidence suggests that financial development is less effective in promoting energy system change in lower-income economies, while its impact strengthens as income rises. For example, Le et al. (2020) and Anton and Afloarei Nucu (2020) found that financial development promotes renewable energy mainly in higher-income economies,

while its impact is weaker or insignificant in lower-income settings. Complementing these findings, Wang and Dong (2021) identified an income threshold beyond which financial development begins to exert a positive and significant effect on renewable energy consumption.

In L/LMICs, shallow financial systems, high energy poverty, weak institutions, and limited absorptive capacity constrain the ability of domestic credit to support large-scale energy diversification. At early stages of development, these constraints limit the scope and pace at which credit-financed investments can translate into a broader energy mix, even when credit availability increases. As income rises, improvements in financial depth—along with associated gains in regulatory quality, technological readiness, and infrastructure—enhance the effectiveness of domestic credit in financing capital-intensive and diversified energy investments. These features suggest that while domestic credit can promote energy diversification, its marginal impact strengthens with economic development, motivating an income-conditioned credit effect.

Therefore, we propose:

*H4: The impact of domestic credit on energy diversification becomes stronger as GDP per capita increases.*

### 3. Methodology and data

#### 3.1. Methodology

##### 3.1.1. Measuring energy diversification

Following the existing literature, including Rubio-Varas and Munoz-Delgado (2019), Akrofi (2020), and Gozgor and Paramati (2022), energy diversification is proxied by the normalized Herfindahl-Hirschman Index (HHI), which is constructed from the shares of primary energy sources. The normalized HHI is obtained by subtracting its minimum possible value  $\left(\frac{1}{n}\right)$  and dividing by its range  $\left(1 - \frac{1}{n}\right)$ . This rescales the index to a range from 0 to 1. A value of 0 indicates perfectly diversified energy consumption (equal shares across all energy sources), whereas a value of 1 indicates complete dependence on a single energy source. For country  $i$  in year  $t$ , energy concentration is defined as:

$$EnergyHHI_i = \frac{\sum_{j=1}^{n_i} \left(\frac{e_{ij}}{E_i}\right)^2 - \frac{1}{n_i}}{1 - \frac{1}{n_i}}, \quad (1)$$

where  $E_i$  denotes total primary energy consumption of country  $i$ , measured in quadrillion British thermal units (BTUs), and  $e_{ij}$  represents energy consumption from source  $j$  in country  $i$ . Accordingly,  $\frac{e_{ij}}{E_i}$  is the share of energy source  $j$  in the total primary energy consumption. The term  $n_i$  denotes the number of energy sources consumed by country  $i$ , including renewable energy, coal, natural gas, petroleum and other liquids, and nuclear.

*EnergyHHI* ranges from 0 to 1, with higher values indicating a greater concentration of primary energy consumption (i.e., greater reliance on a smaller number of energy sources) and lower values indicating a more diversified energy mix. Examining the convergence of *EnergyHHI* reveals whether

countries are becoming more similar in their levels of energy concentration over time. Importantly, convergence itself does not imply either increasing or decreasing energy concentration; rather, it indicates that countries' *EnergyHHI* values are becoming more similar over time. Whether convergence reflects increasing concentration or increasing diversification depends on whether *EnergyHHI* converges to a higher or lower level over time. Understanding these convergence patterns helps identify whether countries are following a common energy transition path or whether groups of countries are converging toward different long-run levels of energy concentration.

The normalized energy HHI is retained as the primary measure throughout the main analysis. To assess the robustness of the findings to the choice of energy diversification measure, the convergence and regression analyses are repeated using an alternative cardinal energy diversification measure, with the results reported in Section 4.4.

### 3.1.2. Convergence of energy diversification

To examine whether energy diversification converges across countries over time, this study adopts the time-varying factor model proposed by Phillips and Sul (2007). This framework allows for heterogeneous transitional dynamics and does not impose a common steady state ex ante.

Energy concentration is decomposed as:

$$EnergyHHI_{it} = \delta_{it}\mu_t, \quad (2)$$

where  $\mu_t$  captures the common component reflecting energy-system trends in L/LMICs and  $\delta_{it}$  is a country-specific, time-varying transition parameter. Relative transition paths are defined as:

$$h_{it} = \frac{EnergyHHI_{it}}{1/N \sum_{i=1}^N EnergyHHI_{it}} = \frac{\delta_{it}}{1/N \sum_{i=1}^N \delta_{it}}, \quad (3)$$

which describes the evolution of each country relative to the panel average. Convergence is assessed using the log-t regression:

$$\log\left(\frac{H_t}{H_{t-1}}\right) - 2 \log(\log t) = \alpha + \gamma \log t + \varepsilon_t, \quad (4)$$

where  $H_t = \frac{1}{N} \sum_{i=1}^N (h_{it} - 1)^2$ . A statistically non-negative  $t$ -statistic for  $\gamma$  indicates convergence, while a significantly negative  $t$ -statistic ( $< -1.65$ ) leads to a rejection of convergence.

When full-panel convergence is rejected, this study follows Phillips and Sul (2009) to identify convergence clubs, defined as groups of countries that converge to distinct steady states in energy concentration. The procedure involves:

- **Initial club formation:** Countries are ranked by their final-period *EnergyHHI*, and an initial core group is identified by sequentially adding countries and estimating the log-t regression. The group that meets the convergence criterion with the highest log-t statistic is selected as the first convergence club. Remaining countries are then used to form additional initial clubs by repeating this procedure, until all convergent groups are identified and any non-convergent countries are classified as divergent.
- **Club merging:** Once initial clubs are identified, pairwise merging tests are conducted to examine whether adjacent clubs share a common convergence path. Clubs are merged when convergence cannot be rejected for the combined group, and the process continues until no further merging is possible, yielding the final club structure and any divergent groups.

This approach accommodates heterogeneity in transitional dynamics and long-run equilibria, making it particularly suitable for countries with diverse energy systems and uneven development levels, such as L/LMICs.

### 3.1.3. The impacts of domestic credit and economic wealth on energy diversification convergence

To examine the determinants of energy diversification, panel regressions are estimated with *EnergyHHI* as the dependent variable. Two alternative measures of financial development (*DomCred*) are employed—domestic credit by financial institutions and domestic credit by banks—which are estimated separately to ensure robustness. The baseline specification is given by:

$$EnergyHHI_{i,t} = \beta_0 + \beta_1 trend + \beta_2 DomCred_{i,t-1} + \beta_3 \ln GDPpc_{i,t-1} + \gamma Z_{i,t-1} + \varphi_i + \varepsilon_{i,t}, \quad (5)$$

where *trend* captures the linear time trend in energy concentration,  $\ln GDPpc$  denotes real GDP per capita, and *Z* is a vector of control variables. The term  $\mu_i$  represents unobserved country-specific effects, while  $\varepsilon_{i,t}$  is the idiosyncratic error term. All explanatory variables are lagged by one period to mitigate potential reverse causality.

To test whether the impact of domestic credit on energy diversification depends on income levels, an interaction term is introduced:

$$EnergyHHI_{i,t} = \beta_0 + \beta_1 trend + \beta_2 DomCred_{i,t-1} + \beta_3 \ln GDPpc_{i,t-1} + \beta_4 DomCred_{i,t-1} * \ln GDPpc_{i,t-1} + \gamma Z_{i,t-1} + \varphi_i + \varepsilon_{i,t}. \quad (6)$$

The interaction coefficient  $\beta_4$  captures how economic development conditions the diversification effect of domestic credit. A positive coefficient implies that the diversification impact of credit weakens as income rises, whereas a negative coefficient suggests that credit becomes more effective at higher income levels.

Based on the literature, the control vector *Z* includes institutional, macroeconomic, and environmental factors commonly associated with energy structure (Diallo and Ouoba, 2024; Islam et al., 2022; Nawaz and Rahman, 2023; Nguyen et al., 2025). Institutional quality is included because governance shapes the policy and investment environment for energy-sector development. Strong institutions facilitate policy implementation, regulatory enforcement, and investment in alternative energy sources, whereas weak institutions may reinforce dependence on existing energy sources (Alharbi et al., 2025; Boubaker et al., 2025). Institutional quality is measured using six governance indicators—Rule of Law, Control of Corruption, Government Effectiveness, Voice and Accountability, Political Stability, and Regulatory Quality—which are entered separately to capture their potentially different effects on energy concentration and to provide a robust assessment of the effects of domestic credit and income. Oil prices are included to capture global energy-market conditions. Gross fixed capital formation proxies investment capacity and infrastructure development, educational attainment reflects human capital, and CO<sub>2</sub> emissions per unit of GDP are included as a measure of emissions efficiency, accounting for cross-country differences in energy-use patterns and fuel composition.

To determine the appropriate panel-data estimator and appropriate standard errors, a set of diagnostic tests is employed. Specifically, the Breusch-Pagan Lagrange multiplier test, the F-test for fixed effects, and the Hausman specification test are used to guide the choice between pooled ordinary least squares (OLS), random effects and fixed effects estimators. In addition, the modified Wald test

for groupwise heteroskedasticity, the Wooldridge test for serial correlation, and the Pesaran test for cross-sectional dependence are conducted to assess potential violations of classical panel assumptions.

### 3.2. Data

This study employs a balanced panel dataset of 46 L/LMICs from 2000 to 2021. Table 1 presents the variables, their definitions, summary statistics, and data sources.

The dependent variable, *EnergyHHI*, averages 0.512 (ranging from 0.080 to 0.999) with a slight decline over time ( $-0.006$ ), suggesting gradual progress toward diversification in several economies. The mean GDP per capita is 1,687 constant 2017 PPP-adjusted US dollars, with substantial dispersion ( $SD = USD\ 1,429$ ), indicating wide income gaps that may shape differing capacities for energy transition and potential convergence clubs. Financial development is represented by domestic credit from financial institutions and banks to the private sector (averaging 27.6% and 25.2% of GDP, respectively). Both show moderate growth, implying an expansion of credit that may facilitate energy investment and diversification.

The control variables capture key economic, environmental, and institutional factors that may influence energy diversification. These include gross fixed capital formation (averaging 22.7% of GDP), oil prices (mean USD 63.97 per barrel), educational attainment (24.3% of the population with upper secondary education), and CO<sub>2</sub> emissions per capita (mean 0.487 metric tons), reflecting investment capacity, exposure to global energy markets, human capital, and emissions intensity. Institutional conditions are accounted for using six governance indicators, each ranging approximately from  $-2.5$  (weak) to  $+2.5$  (strong), which capture cross-country differences in regulatory and governance environments relevant to energy system outcomes.

Table 2 presents pairwise correlations among the main variables. Energy concentration is negatively correlated with domestic credit, gross fixed capital formation, educational attainment, and CO<sub>2</sub> emissions per capita, suggesting that countries with greater credit availability, stronger investment, and higher educational attainment tend to have more diversified energy structures. The correlation with GDP per capita is negative but small, suggesting limited bivariate association. Among the explanatory variables, the highest pairwise correlation is between domestic credit and GDP per capita (0.605), reflecting their close co-movement in L/LMICs. However, this level of correlation is moderate and does not necessarily imply serious multicollinearity. To further assess this issue, we calculate variance inflation factors (VIFs) for both the baseline and interaction models. The maximum VIFs are 2.10 and 2.26, respectively (with mean VIFs of 1.39 and 1.47), which are well below the commonly accepted threshold of 5. These results indicate that multicollinearity is unlikely to affect the estimation results, suggesting that the estimated effects of domestic credit and GDP per capita on energy concentration are unlikely to be driven by multicollinearity.

**Table 1.** Variable definitions, summary statistics, and data sources.

| Variables                                                                                                                      | Definition                                                                                                                    | Mean     | SD       | Min     | Max      | Growth<br>(2000–2021) | Data<br>source |
|--------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------|----------|----------|---------|----------|-----------------------|----------------|
| <i>Energy HHI</i>                                                                                                              | Measures energy concentration using the normalized HHI across five energy sources                                             | 0.512    | 0.258    | 0.080   | 0.999    | −0.006                | *** EIA        |
| <i>GDP pc</i>                                                                                                                  | Gross Domestic Product per person, adjusted for purchasing power parity (PPP\$), in inflation-adjusted US dollars (thousands) | 1687.657 | 1428.730 | 255.100 | 9037.086 | 35.637                | *** WDI        |
| <i>Financial Institution Development</i>                                                                                       |                                                                                                                               |          |          |         |          |                       |                |
| <i>Dom Credit by FIs</i>                                                                                                       | Refers to domestic credit by financial institutions to the private sector, as a percentage of GDP (%)                         | 27.601   | 24.372   | 0.002   | 166.262  | 0.785                 | *** WDI        |
| <i>Dom Credit by Banks</i>                                                                                                     | Refers to domestic credit by banks to the private sector, as a percentage of GDP (%)                                          | 25.168   | 22.158   | 0.002   | 166.240  | 0.915                 | *** WDI        |
| <b><i>Institutional Governance Indicators:</i></b> <i>The estimate ranges approximately from −2.5 (weak) to +2.5 (strong).</i> |                                                                                                                               |          |          |         |          |                       |                |
| <i>Rule of Law</i>                                                                                                             | Reflects public confidence in legal institutions, protection of property rights, and the fairness of law enforcement          | −0.717   | 0.517    | −2.096  | 1.271    | −0.000                | WDI            |
| <i>Political Stability</i>                                                                                                     | Indicates the likelihood of political unrest or violence that could undermine government stability                            | −0.760   | 0.770    | −2.965  | 1.283    | −0.003                | WDI            |
| <i>Corrupt Control</i>                                                                                                         | Measures the extent to which public power is used for private benefit and how effectively corruption is curbed                | −0.742   | 0.443    | −1.798  | 0.776    | −0.001                | WDI            |
| <i>Gov. Effectiveness</i>                                                                                                      | Assesses the competence of public services and the government's ability to implement sound policies                           | −0.708   | 0.478    | −1.851  | 0.707    | −0.001                | WDI            |
| <i>Voice &amp; Account</i>                                                                                                     | Captures citizens' freedom to participate in governance, express opinions, and access independent media                       | −0.685   | 0.644    | −2.124  | 0.797    | 0.001                 | WDI            |
| <i>Reg Quality</i>                                                                                                             | Shows how well government regulations support private enterprise and promote market efficiency                                | −0.701   | 0.437    | −2.243  | 0.191    | −0.002                | WDI            |
| <b><i>Control Variables</i></b>                                                                                                |                                                                                                                               |          |          |         |          |                       |                |
| <i>Oil Price</i>                                                                                                               | Crude oil price, measured by West Texas Intermediate (WTI), in US dollars (\$)                                                | 63.971   | 23.795   | 25.933  | 99.565   | 1.214                 | *** FRED       |
| <i>Capital Form</i>                                                                                                            | Gross fixed capital formation, which reflects the investment in fixed assets in an economy as a percentage of GDP (%)         | 22.718   | 8.193    | 1.097   | 78.001   | 0.271                 | *** WDI        |
| <i>Edu Attain</i>                                                                                                              | Percentage of the population with upper secondary education (%)                                                               | 24.293   | 18.687   | 6.975   | 67.570   | 0.027                 | WDI            |
| <i>CO<sub>2</sub> Emissions</i>                                                                                                | The average amount of carbon dioxide (CO <sub>2</sub> ) emitted per person per year, measured in metric tons                  | 0.487    | 0.455    | 0.062   | 3.934    | −0.001                | WDI            |

Notes: WDI = World Development Indicators (World Bank); EIA = U.S. Energy Information Administration; FRED = Federal Reserve Economic Data. \*\*\* and \*\*: 1% and 5% level of significance, respectively.

**Table 2.** Pairwise correlations between variables.

| Variables                                         | (1)       | (2)      | (3)      | (4)      | (5)      | (6)      | (7)    | (8)   |
|---------------------------------------------------|-----------|----------|----------|----------|----------|----------|--------|-------|
| (1) <i>Energy HHI<sub>t</sub></i>                 | 1.000     |          |          |          |          |          |        |       |
| (2) <i>Dom Credit by FIs<sub>t-1</sub></i>        | −0.134*** | 1.000    |          |          |          |          |        |       |
| (3) <i>Log(GDP pc)<sub>t-1</sub></i>              | −0.098*** | 0.605*** | 1.000    |          |          |          |        |       |
| (4) <i>Log(Oil Price)<sub>t-1</sub></i>           | −0.031    | 0.015    | 0.080**  | 1.000    |          |          |        |       |
| (5) <i>Capital Form<sub>t-1</sub></i>             | −0.104*** | 0.141*** | 0.284*** | 0.153*** | 1.000    |          |        |       |
| (6) <i>Educ Attain<sub>t-1</sub></i>              | −0.115*** | 0.274*** | 0.420*** | −0.008   | −0.034   | 1.000    |        |       |
| (7) <i>CO<sub>2</sub> Emissions<sub>t-1</sub></i> | −0.176*** | 0.139*** | 0.340*** | −0.028   | 0.087*** | 0.316*** | 1.000  |       |
| (8) <i>Rule of Law<sub>t-1</sub></i>              | 0.065**   | 0.339*** | 0.281*** | −0.039   | 0.111*** | 0.163*** | −0.040 | 1.000 |

\*\*\*, \*\*, and \*: 1%, 5%, and 10% level of significance, respectively.

## 4. Empirical results

### 4.1. Convergence of energy diversification

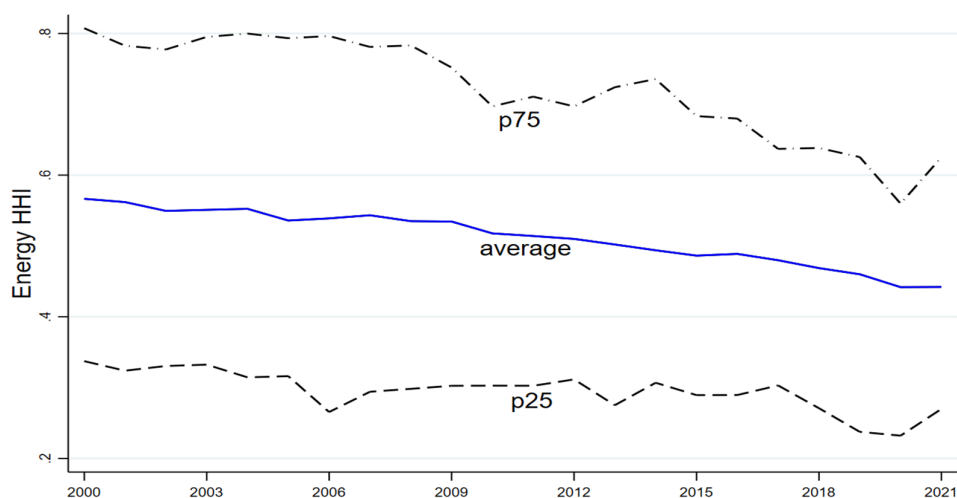
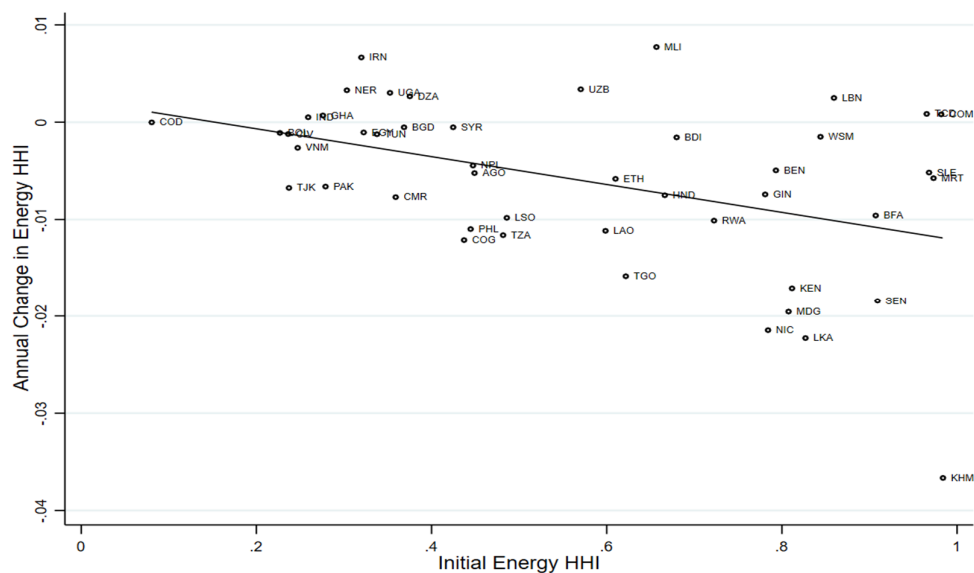
Figure 1 and Table 3 present the trends and summary statistics of the *EnergyHHI* for 46 L/LMICs from 2000 to 2021. The mean *EnergyHHI* declined from 0.57 to 0.44 (−0.006 annually), indicating a gradual move toward more diversified energy structures. The 25th, 50th, and 75th percentiles also show consistent downward trends, reflecting overall progress in diversification, though at an uneven pace across countries.

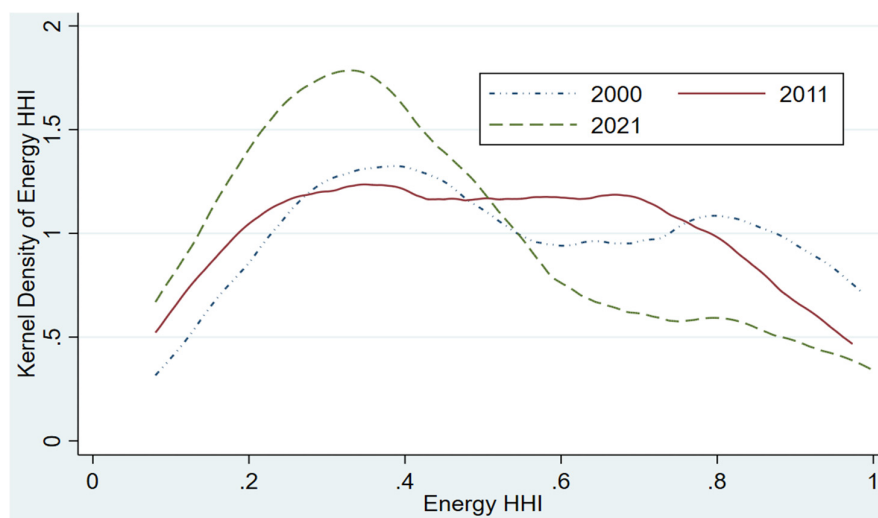
Both the slight narrowing of the gap between the 25th and 75th percentiles (from 0.47 to 0.36) and the small decline in the standard deviation (from 0.26 to 0.24) suggest a modest reduction in cross-country disparity. These shifts point to a slow and partial tendency toward convergence, though the remaining variation implies that distinct convergence clubs may still emerge among countries with similar economic and institutional characteristics.

Figure 2 shows a negative relationship between the annual change in the *EnergyHHI* and its initial level in 2000, indicating that countries with a higher initial concentration have generally diversified faster—suggesting a tendency toward  $\beta$ -convergence, although the wide dispersion of observations points to only partial convergence. Figure 3 further supports this trend: the *EnergyHHI* distributions shift leftward from 2000 to 2021, showing overall progress in diversification. The presence of several peaks across years indicates persistent heterogeneity and possible clustering of countries at different diversification levels, while the higher kernel density in 2021 around lower *EnergyHHI* values suggests that an increasing number of economies have moved toward more diversified energy structures. These features point to gradual but uneven convergence, with potential formation of convergence clubs.

**Table 3.** Descriptive statistics for *EnergyHHI*.

|                       | <i>EnergyHHI</i> 2000 | <i>EnergyHHI</i> 2021 | Annual change |
|-----------------------|-----------------------|-----------------------|---------------|
| mean                  | 0.57                  | 0.44                  | −0.0060       |
| standard deviation    | 0.26                  | 0.24                  | −0.0008       |
| p25 (25th percentile) | 0.34                  | 0.27                  | −0.0027       |
| p50 (median)          | 0.53                  | 0.37                  | −0.0080       |
| p75 (75th percentile) | 0.81                  | 0.63                  | −0.0079       |

**Figure 1.** Trends in *EnergyHHI*, 2000–2021.**Figure 2.**  $\beta$ -Convergence in *EnergyHHI*, 2000–2021.



**Figure 3.** Shifts in *EnergyHHI* distributions over time.

Table 4 presents the results of the overall convergence tests for the *EnergyHHI* using  $\beta$ -,  $\sigma$ -, and log-t approaches. The  $\beta$ -convergence coefficient is negative and statistically significant ( $-0.140$ ,  $p < 0.01$ ), indicating that countries with higher initial energy concentration have tended to diversify faster over time. This finding is consistent with the negative slope observed earlier in Figure 2. The  $\sigma$ -convergence coefficient is also negative and significant ( $-0.161$ ,  $p < 0.01$ ), suggesting a modest decline in cross-country dispersion. This finding aligns with the slight fall in the standard deviation and narrower interquartile range in Table 3, as well as the distributional shifts in Figure 3, where countries show gradual though uneven movement toward greater diversification.

However, the highly negative log-t statistic ( $-39.456$ ) rejects the null hypothesis of full convergence, implying that economies do not converge toward a single steady-state level of diversification. Taken together, these results point to partial convergence in energy diversification across 46 L/LMICs, with evidence suggesting the possible formation of convergence clubs among groups of economies sharing similar structural, financial, or institutional characteristics.

**Table 4.** Overall convergence tests (beta, sigma, and log-t) for *EnergyHHI*.

| Tests            | $\beta$ test   |          | $\sigma$ test  |          | $\gamma$ test (log-t test) |           |
|------------------|----------------|----------|----------------|----------|----------------------------|-----------|
|                  | Coef           | t-stat   | Coef           | t-stat   | Coef.                      | t-stat    |
| <i>EnergyHHI</i> | $-0.140^{***}$ | $-8.106$ | $-0.161^{***}$ | $-8.851$ | $-0.989$                   | $-39.456$ |

$\beta$  and  $\sigma$  tests: \*\*\* denotes significance at the 1% level.

$\gamma$  test: The null hypothesis of convergence is rejected at the 5% significance level if the t-statistic is below  $-1.65$ .

Having rejected overall convergence in the log-t test, we next apply the Phillips and Sul (2007, 2009) algorithm to identify groups of countries that share similar long-run diversification paths. Table 5 summarizes the sequential steps of this procedure, including the initial club formation, the set of club-merging tests, and the resulting final classification. The initial algorithm identifies six convergence clubs and one divergent economy. After applying the merging procedure, which tests whether adjacent clubs can be merged to form larger clubs, the classification results in three stable

convergence clubs and one divergent country, which implies three distinct long-run equilibrium levels of energy diversification among 46 L/LMICs. Club 1 (17 members,  $\log-t = -0.136$ ) displays relatively slow convergence toward a higher equilibrium of energy diversification, suggesting limited diversification progress. Club 2 (23 members,  $\log-t = 0.078$ ) shows moderate convergence toward an intermediate diversification level. In contrast, Club 3 (five members,  $\log-t = 0.983$ ) exhibits the strongest convergence dynamics, moving toward a more diversified energy structure. Senegal remains an outlier, diverging from all identified clubs.

**Table 5.** Convergence club classification for *EnergyHHI*.

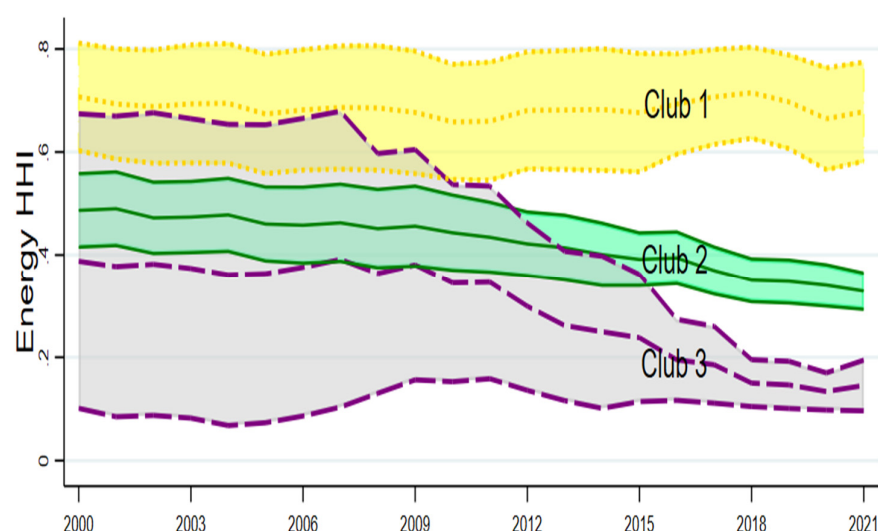
| Initial classification |         |       |        | Tests of club merging |         |        |        | Final club classification |         |        |        | Final Clubs'         |
|------------------------|---------|-------|--------|-----------------------|---------|--------|--------|---------------------------|---------|--------|--------|----------------------|
| Covergence             | Members | Log-t | t-stat | Covergence            | Members | Log-t  | t-stat | Covergence                | Members | Log-t  | t-stat | Memberships          |
| Clubs                  |         |       |        | Clubs                 |         |        |        | Clubs                     |         |        |        |                      |
| Club 1                 | 5       | 0.267 | 0.919  |                       |         |        |        | Club 1                    | 17      | -0.136 | -1.361 | Algeria, Benin,      |
| Club 2                 | 7       | 0.205 | 2.117  | Clubs 1+2             | 12      | 0.158  | 0.770  |                           |         |        |        | Burkina Faso,        |
| Club 3                 | 5       | 0.646 | 4.488  | Clubs 2+3             | 12      | -0.096 | -2.542 |                           |         |        |        | Burundi, Chad,       |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Comoros, Guinea,     |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Iran, Islamic Rep.,  |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Lao PDR, Lebanon,    |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Mali, Mauritania,    |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Nepal, Niger,        |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Samoa, Sierra        |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Leone, Uzbekistan    |
| Club 4                 | 7       | 0.272 | 2.047  | Clubs 3+4             | 12      | 0.362  | 3.058  | Club 2                    | 23      | 0.078  | 0.664  | Angola,              |
| Club 5                 | 16      | 0.370 | 2.469  | Clubs 4+5             | 23      | 0.078  | 0.664  |                           |         |        |        | Bangladesh,          |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Bolivia, Congo       |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Rep., Cote d'Ivoire, |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Egypt, Arab Rep.,    |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Ethiopia, Ghana,     |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Honduras, India,     |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Kenya, Lesotho,      |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Madagascar,          |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Nicaragua,           |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Philippines,         |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Rwanda, Sri Lanka,   |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Syrian Arab          |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Republic, Tanzania,  |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Togo, Tunisia,       |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Uganda, Viet Nam     |
| Club 6                 | 5       | 0.983 | 8.512  | Clubs 5+6             | 21      | -0.077 | -2.239 | Club 3                    | 5       | 0.983  | 8.512  | Cambodia,            |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Cameroon, Congo      |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Dem. Rep.,           |
|                        |         |       |        |                       |         |        |        |                           |         |        |        | Pakistan, Tajikistan |
| Divergence             | 1       |       |        | Club                  | 6       | -1.201 | -9.262 | Divergence                | 1       |        |        | Senegal              |
|                        |         |       |        | 6+Diver               |         |        |        |                           |         |        |        |                      |

The null hypothesis of convergence is rejected at the 5% significance level if the t-statistic is below  $-1.65$ .

Table 6 and Figure 4 provide further features of the long-run patterns of energy diversification across the three final convergence clubs and the divergent group. The average *EnergyHHI* in 2000 and 2021 show that each club follows a distinct trajectory and converges toward a different long-run diversification equilibrium. Club 1 maintains the highest concentration levels, decreasing only slightly from 0.71 in 2000 to 0.68 in 2021, consistent with the small annual change ( $-0.0014$ ). Its relatively flat path in Figure 4, along with a wide and stable 90% confidence band, shows that member countries remain quite different from one another and are converging only slowly toward a relatively high concentration equilibrium. Club 2 starts at an intermediate concentration level (0.49 in 2000) and declines to 0.33 by 2021, in line with its larger annual reduction ( $-0.0075$ ). The downward trend in Figure 4 indicates a steady move toward greater diversification. The gradual narrowing of the 90% confidence band suggests that members are becoming more similar over time, pointing to convergence toward a moderate concentration equilibrium. Club 3 exhibits the lowest concentration levels and the fastest progress, falling from 0.39 in 2000 to 0.15 in 2021, consistent with the steep annual change ( $-0.0115$ ). Its sharply declining path in Figure 4 signals a rapid shift toward more diversified energy structures. The marked tightening of its 90% confidence band shows increasing similarity among members, reflecting strong convergence toward a low concentration (highly diversified) equilibrium. The divergent economy (Senegal) shows a decline in concentration but does not align with any club's long-run path.

**Table 6.** Average *EnergyHHI* by convergence club, 2000 and 2021.

|                 | Number of countries | <i>EnergyHHI</i> (average) |      |               |
|-----------------|---------------------|----------------------------|------|---------------|
|                 |                     | 2000                       | 2021 | Annual change |
| Club 1          | 17                  | 0.71                       | 0.68 | $-0.0014$     |
| Club 2          | 23                  | 0.49                       | 0.33 | $-0.0075$     |
| Club 3          | 5                   | 0.39                       | 0.15 | $-0.0115$     |
| Divergent group | 1                   | 0.91                       | 0.52 | $-0.0184$     |
| Full sample     | 46                  | 0.57                       | 0.44 | $-0.0060$     |



**Figure 4.** *EnergyHHI* paths and 90% confidence intervals by convergence clubs.

The heterogeneous convergence patterns observed among 46 L/LMICs suggest that these countries do not follow a common energy diversification pathway but instead converge toward different long-run equilibria. One possible explanation is path dependence in national energy systems, where initial energy structures shape future diversification paths (Karanfil and Omgba, 2023). According to the carbon lock-in theory, countries can become trapped in fossil-fuel-based energy systems because infrastructure, technologies, and investment have developed around these energy sources, making the transition to alternative energy sources more difficult and costly (Unruh, 2000). As a result, countries that initially rely heavily on fossil fuels are more likely to remain dependent on them, while those with more diversified energy structures are better positioned to expand alternative energy sources. However, the expansion of alternative energy sources may be limited where supportive legislation, policy incentives, or investment resources are lacking. Without an enabling policy and investment environment, the adoption of cleaner energy technologies is slower, allowing countries to remain in lower-diversification equilibria (Achuo et al., 2024; Presno and Landajo, 2021). Together, these mechanisms provide a plausible explanation for why countries with different initial energy structures converge toward different long-run diversification paths rather than a single common equilibrium.

To further characterize the identified convergence clubs, Table 7 compares their initial energy, economic, financial, and institutional characteristics in 2000. Consistent with the path-dependence and carbon lock-in mechanisms discussed above, the clubs are distinguished most clearly by their initial energy structures. Club 1, which converges toward the highest long-run energy concentration, records the highest initial *EnergyHHI*, the greatest reliance on petroleum and other liquids, and the lowest renewable energy share. In contrast, Club 3, which converges toward the lowest long-run energy concentration, exhibits the lowest initial *EnergyHHI*, the lowest dependence on petroleum and other liquids, and the highest renewable energy share, while Club 2 occupies an intermediate position. These patterns are consistent with the view that countries entering the sample with more fossil-fuel-dependent energy systems may face greater difficulty in shifting toward more diversified structures, whereas countries with initially more diversified energy mixes may be better positioned to expand alternative energy sources (Achuo et al., 2024; Karanfil and Omgba, 2023; Presno and Landajo, 2021). GDP per capita also displays an ordering across the club averages, with Club 1 recording the highest initial income level and Club 3 the lowest. However, these averages do not reveal the relationship between income and energy concentration, which depends on variation across countries and over time. Similarly, domestic credit and government effectiveness cannot be interpreted conclusively from the descriptive averages alone. Their relationships with energy diversification are therefore examined more systematically in the panel regression analyses presented in Sections 4.2 and 4.3.

**Table 7.** Initial characteristics of the identified convergence clubs (2000).

| Variable                                               | Club 1   | Club 2   | Club 3  |
|--------------------------------------------------------|----------|----------|---------|
| <i>EnergyHHI</i>                                       | 0.685    | 0.424    | 0.293   |
| Petroleum and other liquids share (%)                  | 78.291   | 67.633   | 54.482  |
| Renewable share (%)                                    | 5.433    | 8.132    | 24.494  |
| GDP per capita (constant 2017 PPP-adjusted US dollars) | 1915.530 | 1696.892 | 966.737 |
| Domestic credit by FIs to GDP (%)                      | 25.917   | 30.335   | 21.936  |
| Government effectiveness                               | −0.812   | −0.583   | −1.003  |

#### 4.2. The impacts of domestic credit and economic wealth on energy diversification convergence

Before estimating the panel regression models, unit root tests were conducted for all variables. The results, reported in Appendix Table A1, provide mixed evidence on the stationarity of the variables at levels across different panel unit root tests. However, all variables are found to be stationary after first differencing. Given the evidence of unit-root behavior for several variables, the Pedroni panel cointegration test was further conducted to examine whether a stable long-run relationship exists among the variables. As reported in Appendix Table A2, all three Pedroni test statistics reject the null hypothesis of no cointegration at the 1% significance level, indicating the existence of a long-run equilibrium relationship among the variables. These findings provide further support for estimating the panel regression models in levels.

Table 8 reports the diagnostic tests used for model selection. Both the Breusch-Pagan LM test and the F-test reject the pooled OLS specification in favor of a panel-data approach, while the Hausman test favors fixed effects over random effects. Further diagnostics indicate heteroskedasticity and serial correlation, with only limited evidence of cross-sectional dependence. Accordingly, the analysis employs fixed-effects estimations with Driscoll-Kraay standard errors to ensure robustness to these features of the error structure.

**Table 8.** Diagnosis tests.

| Diagnosis tests                                          | Financial Development         |     |                                 |     |
|----------------------------------------------------------|-------------------------------|-----|---------------------------------|-----|
|                                                          | <i>Domestic Credit by FIs</i> |     | <i>Domestic Credit by Banks</i> |     |
| <i>Tests for determining an appropriate estimator</i>    |                               |     |                                 |     |
| Breusch and Pagan test for random effects                | 7,034.04                      | *** | 7,012.53                        | *** |
| F-test for fixed effects                                 | 154.90                        | *** | 153.07                          | *** |
| Hausman test for random effects versus fixed effects     | 61.78                         | *** | 50.38                           | *** |
| <i>Tests for determining appropriate standard errors</i> |                               |     |                                 |     |
| Modified Wald test for heteroskedasticity                | 9,075.52                      | *** | 12,293.02                       | *** |
| Pesaran test for cross-sectional dependence              | 0.35                          |     | 0.71                            |     |
| Wooldridge test for autocorrelation                      | 37.87                         | *** | 37.79                           | *** |

\*\*\*: 1% level of significance.

Table 9 presents estimates of the effects of domestic credit and economic development on energy diversification, measured by the *EnergyHHI*. The coefficient on the time trend is negative and statistically significant across all specifications, indicating a sustained decline in energy concentration over the sample period. This pattern suggests a gradual shift toward more diversified energy mixes among L/LMICs, consistent with the trends discussed in Section 4.1.

Across all models, lagged domestic credit—whether measured as credit from financial institutions or banks—remains negative and statistically significant. This suggests that deeper and more accessible financial systems support diversification by easing investment in alternative energy sources, favoring Hypothesis 2. Recent work shows that financial institutions are increasingly reallocating capital toward renewable energy projects (Li, 2023; Mukhtarov et al., 2022), while improvements in financial efficiency strengthen capital flows to clean energy in both emerging and advanced economies (Alsagr, 2023). Advances in technology also help accelerate the shift toward clean energy (Aydin and Bozatli, 2023; Dogan et al., 2022). Consistent with this evidence, financial development has been shown to

promote clean-energy transitions in emerging markets (Diallo and Ouoba, 2024; Nchofoung, 2024). As renewable capacity expands, the energy mix naturally broadens and concentration declines (Liu et al., 2023), consistent with the pattern identified in our estimates.

Economic development, proxied by lagged GDP per capita, also displays a negative and statistically significant coefficient. This suggests that wealthier economies within the sample diversify more rapidly, supporting Hypothesis 3. Existing evidence supports this mechanism: as income rises, countries are better able to invest in low-carbon technologies, expand renewable energy capacity, and upgrade outdated energy infrastructure (Eren et al., 2019; Murshed and Tanha, 2021; Saadaoui and Chtourou, 2023). The results therefore align with the broader view that economic development facilitates structural change away from concentrated fossil-fuel systems.

The results for institutional quality contrast with findings from higher-income settings. All governance indicators enter with positive coefficients, and several—such as Control of Corruption, Voice and Accountability, and Regulatory Quality—are significant, implying that stronger institutions are linked to higher energy concentration rather than diversification. This pattern has several explanations. In many L/LMICs, fossil-fuel systems benefit from established infrastructure, lower investment risk, and reliable output, making them attractive to policymakers and investors. Renewables, by contrast, often require large upfront capital, face higher financial and technological risks, and depend on policies that are not yet fully developed<sup>2</sup>. As a result, improvements in governance may stabilize existing fossil-fuel pathways rather than promote alternatives. Recent studies similarly show that stronger institutions can reinforce incumbent energy systems when political incentives and economic structures favor fossil fuels and when energy transitions remain slow (Islam et al., 2022; Mahdavi et al., 2022; Pasandideh and Ezaan, 2025).

Lagged oil prices have a positive and significant effect on the *EnergyHHI*, indicating that higher oil prices are associated with greater energy concentration. This likely reflects the continued reliance of these economies on oil-intensive sectors. The result is consistent with Nchofoung (2024), who found that oil price shocks impede clean energy transitions in African countries. It also aligns with Murshed and Tanha (2021), who showed that higher oil prices do not initially promote renewable energy use in South Asia and only stimulate renewables beyond a high price threshold (around USD 135 per barrel). Since oil prices in our sample remain well below this threshold, rising prices tend to reinforce dependence on dominant fossil-fuel sources.

Gross fixed capital formation consistently carries a negative and statistically significant coefficient across all models, indicating that higher investment levels in infrastructure are associated with lower energy concentration. This suggests that capital accumulation supports structural upgrading, expansion of new energy infrastructure, and gradual broadening of the energy mix—consistent with evidence that gross fixed capital formation is critical in amplifying clean energies in the energy mix (Kor and Qamruzzaman, 2023).

Educational attainment enters with a positive and significant coefficient, indicating that higher education levels are associated with greater energy concentration rather than diversification. While education supports long-run technological progress, evidence from low-income countries suggests that rising human capital initially increases demand for modern commercial energy, which remains largely

<sup>2</sup> <https://www.iea.org/reports/financing-clean-energy-transitions-in-emerging-and-developing-economies> and <https://www.iea.org/reports/world-energy-investment-2024>.

carbon-intensive. For example, Oluoch et al. (2021) showed that higher education in sub-Saharan Africa is linked to greater conventional energy use, while Bello et al. (2021) found that increased school enrollment raises consumption of carbon-emitting energy sources. Where renewable infrastructure is limited, improvements in education may therefore reinforce reliance on existing fossil-fuel systems instead of broadening the energy mix.

Lastly, CO<sub>2</sub> emissions per unit of GDP carry a small and generally insignificant coefficient, indicating no systematic relationship between carbon intensity and energy diversification. This suggests that carbon intensity alone does not drive meaningful changes in the structure of the energy mix. While studies such as Murshed and Tanha (2021) showed that environmental pressures can encourage renewable energy adoption, this response appears much weaker in low-income countries. Structural constraints, limited renewable capacity, and continued reliance on conventional fuels likely mute the link between carbon intensity and diversification across the sample.

**Table 9.** The impacts of domestic credit and GDP per capita on *EnergyHHI*.

| Domestic credit                 | <i>Domestic Credit by Fis</i> |           |           |           |           |           | <i>Domestic Credit by Banks</i> |           |           |           |           |           |
|---------------------------------|-------------------------------|-----------|-----------|-----------|-----------|-----------|---------------------------------|-----------|-----------|-----------|-----------|-----------|
|                                 | (1)                           | (2)       | (3)       | (4)       | (5)       | (6)       | (7)                             | (8)       | (9)       | (10)      | (11)      | (12)      |
| <i>Trend</i>                    | −0.003***                     | −0.003*** | −0.003*** | −0.004*** | −0.003*** | −0.003*** | −0.003***                       | −0.003*** | −0.003*** | −0.003*** | −0.003*** | −0.003*** |
| <i>Dom Credit</i>               | −0.145***                     | −0.137*** | −0.148*** | −0.148*** | −0.146*** | −0.144*** | −0.149***                       | −0.132*** | −0.151*** | −0.147*** | −0.150*** | −0.149*** |
| <i>lnGDP pc</i>                 | −0.062***                     | −0.071*** | −0.054*** | −0.051*** | −0.048*** | −0.066*** | −0.060***                       | −0.069*** | −0.051*** | −0.047*** | −0.048*** | −0.063*** |
| <i>LnOil Price</i>              | 0.012**                       | 0.013**   | 0.011**   | 0.012***  | 0.010**   | 0.010*    | 0.013***                        | 0.015***  | 0.012**   | 0.013***  | 0.012**   | 0.011**   |
| <i>Capital Form</i>             | −0.113**                      | −0.140**  | −0.115*   | −0.117**  | −0.111**  | −0.111**  | −0.110**                        | −0.136**  | −0.112*   | −0.112**  | −0.110**  | −0.108*   |
| <i>Educ Attain</i>              | 0.054**                       | 0.055**   | 0.048**   | 0.065**   | 0.049**   | 0.045**   | 0.063**                         | 0.063***  | 0.057**   | 0.074**   | 0.057**   | 0.054**   |
| <i>CO<sub>2</sub> Emissions</i> | 0.001                         | −0.004    | 0.002     | 0.004     | 0.001     | 0.004     | 0.000                           | −0.005    | 0.002     | 0.003     | 0.001     | 0.004     |
| <i>Rule of Law</i>              | 0.025                         |           |           |           |           |           | 0.028                           |           |           |           |           |           |
| <i>Corrupt Control</i>          |                               | 0.055**   |           |           |           |           |                                 | 0.055**   |           |           |           |           |
| <i>Gov. Effectiveness</i>       |                               |           | 0.015     |           |           |           |                                 |           | 0.016     |           |           |           |
| <i>Voice &amp; Account</i>      |                               |           |           | 0.056**   |           |           |                                 |           |           | 0.055**   |           |           |
| <i>Political Stability</i>      |                               |           |           |           | 0.002     |           |                                 |           |           |           | 0.005     |           |
| <i>Reg Quality</i>              |                               |           |           |           |           | 0.040***  |                                 |           |           |           |           | 0.044***  |
| <i>Constant</i>                 | 1.012***                      | 1.098***  | 0.958***  | 0.951***  | 0.904***  | 1.055***  | 0.985***                        | 1.067***  | 0.923***  | 0.914***  | 0.894***  | 1.027***  |
| <i>Observations</i>             | 966                           | 966       | 966       | 966       | 966       | 966       | 966                             | 966       | 966       | 966       | 966       | 966       |

All explanatory and control variables, except the trend variable, are lagged by one year. \*\*\*, \*\*, and \* denote statistical significance at the 1%, 5%, and 10% levels, respectively.

To examine whether the relationship between economic development and energy diversification is nonlinear, we estimate an additional specification that includes both the linear and squared terms of GDP per capita. As reported in Table 10, the coefficient on the linear term of lnGDP per capita is negative and statistically significant, whereas the coefficient on its squared term is positive and statistically significant across all specifications. Because the dependent variable is the *EnergyHHI*, with higher values indicating greater energy concentration, these results imply a U-shaped relationship between GDP per capita and energy concentration. Equivalently, they indicate an inverted U-shaped relationship between GDP per capita and energy diversification, consistent with the nonlinear relationship discussed in the literature (e.g., Hajko et al. (2018) and Nibedita and Irfan (2024)).

The estimated turning point is approximately \$2203 (2017 PPP)<sup>3</sup>. Below this threshold, increases in GDP per capita are associated with lower energy concentration (greater energy diversification). Beyond this threshold, further increases in GDP per capita are associated with higher energy concentration (lower energy diversification). Approximately 76% of the country-year observations lie below the estimated turning point<sup>4</sup>, suggesting that for most observations in the sample of L/LMICs, economic development is associated with greater energy diversification. Importantly, the estimated coefficient on domestic credit remains negative and statistically significant after accounting for the nonlinear income effect. This indicates that the main finding regarding the relationship between domestic credit and energy concentration is qualitatively unchanged.

**Table 10.** Nonlinear effect of GDP per capita on *EnergyHHI*.

| Domestic credit                 | <i>Domestic Credit by Fis</i> |           |           |           |           | <i>Domestic Credit by Banks</i> |           |           |           |           |           |           |
|---------------------------------|-------------------------------|-----------|-----------|-----------|-----------|---------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| Models                          | (1)                           | (2)       | (3)       | (4)       | (5)       | (6)                             | (7)       | (8)       | (9)       | (10)      | (11)      | (12)      |
| <i>Trend</i>                    | −0.003***                     | −0.003*** | −0.004*** | −0.004*** | −0.004*** | −0.003***                       | −0.003*** | −0.003*** | −0.003*** | −0.004*** | −0.004*** | −0.003*** |
| <i>Dom Credit</i>               | −0.160***                     | −0.151*** | −0.161*** | −0.162*** | −0.160*** | −0.158***                       | −0.178*** | −0.158*** | −0.176*** | −0.172*** | −0.174*** | −0.176*** |
| <i>lnGDP pc</i>                 | −0.731***                     | −0.746*** | −0.642*** | −0.654*** | −0.634**  | −0.701***                       | −0.766*** | −0.763*** | −0.667*** | −0.675*** | −0.659*** | −0.733*** |
| <i>(lnGDP pc)<sup>2</sup></i>   | 0.047***                      | 0.048***  | 0.042**   | 0.043***  | 0.042**   | 0.045***                        | 0.050***  | 0.050***  | 0.044***  | 0.045***  | 0.044***  | 0.048***  |
| <i>LnOil Price</i>              | 0.013***                      | 0.014***  | 0.011**   | 0.013***  | 0.010**   | 0.010*                          | 0.015***  | 0.015***  | 0.012**   | 0.014***  | 0.012**   | 0.011**   |
| <i>Capital Form</i>             | −0.083                        | −0.112    | −0.087    | −0.087    | −0.081    | −0.081                          | −0.079    | −0.107    | −0.083    | −0.082    | −0.080    | −0.076    |
| <i>Educ Attain</i>              | 0.055*                        | 0.055**   | 0.047**   | 0.065**   | 0.049**   | 0.044*                          | 0.065**   | 0.064***  | 0.057**   | 0.074**   | 0.057**   | 0.053**   |
| <i>CO<sub>2</sub> Emissions</i> | 0.013                         | 0.008     | 0.013     | 0.015     | 0.012     | 0.016                           | 0.014     | 0.008     | 0.014     | 0.015     | 0.013     | 0.018     |
| <i>Rule of Law</i>              | 0.037*                        |           |           |           |           |                                 | 0.041**   |           |           |           |           |           |
| <i>Corrupt Control</i>          |                               | 0.064***  |           |           |           |                                 |           | 0.063***  |           |           |           |           |
| <i>Gov. Effectiveness</i>       |                               |           | 0.015     |           |           |                                 |           |           | 0.016     |           |           |           |
| <i>Voice &amp; Account</i>      |                               |           |           | 0.058**   |           |                                 |           |           |           | 0.056**   |           |           |
| <i>Political Stability</i>      |                               |           |           |           | 0.001     |                                 |           |           |           |           | 0.004     |           |
| <i>Regulatory Quality</i>       |                               |           |           |           |           | 0.046***                        |           |           |           |           |           | 0.050***  |
| <i>Constant</i>                 | 3.336***                      | 3.430***  | 2.971***  | 3.019***  | 2.907***  | 3.247***                        | 3.433***  | 3.456***  | 3.027***  | 3.058***  | 2.977***  | 3.332***  |
| <i>Observations</i>             | 966                           | 966       | 966       | 966       | 966       | 966                             | 966       | 966       | 966       | 966       | 966       | 966       |

All explanatory and control variables, except the trend variable, are lagged by one year. \*\*\*, \*\*, and \* denote statistical significance at the 1%, 5%, and 10% levels, respectively.

To further examine the role of foreign investment, we extend the nonlinear specification by including net FDI inflows as an additional control variable. As reported in Appendix Table A3, net FDI inflows are negatively and statistically significantly associated with the *EnergyHHI* across all

<sup>3</sup> The turning point is calculated as  $-\beta_1/(2 * \beta_2)$ , where  $\beta_1$  and  $\beta_2$  are the estimated coefficients on the linear and squared terms of log GDP per capita, respectively. Because the model is estimated using the natural logarithm of GDP per capita, the estimated turning point is converted into GDP per capita in levels by applying the exponential transformation, GDP per capita = exp(turning point).

<sup>4</sup> The percentage is calculated using all country-year observations over the 2000–2021 sample period. An observation is classified as below the turning point if its GDP per capita is less than the estimated threshold of 2202 constant 2017 PPP-adjusted US dollars.

specifications, suggesting that greater foreign investment is associated with lower energy concentration and, therefore, greater energy diversification. This finding is consistent with the view that foreign investment facilitates energy diversification by improving access to capital, technologies, and productive capacity. Importantly, the estimated effects of domestic credit, GDP per capita, and the nonlinear income term remain qualitatively unchanged after controlling for net FDI inflows, indicating that the main conclusions are robust to the inclusion of foreign investment.

#### *4.3. Income effects on the domestic credit-energy diversification link*

To examine whether the effect of domestic credit on energy diversification varies across income levels, the model includes an interaction term between domestic credit and income. Both variables are mean-centered prior to estimation to improve coefficient interpretation and reduce multicollinearity. The full set of results is reported in Table 11.

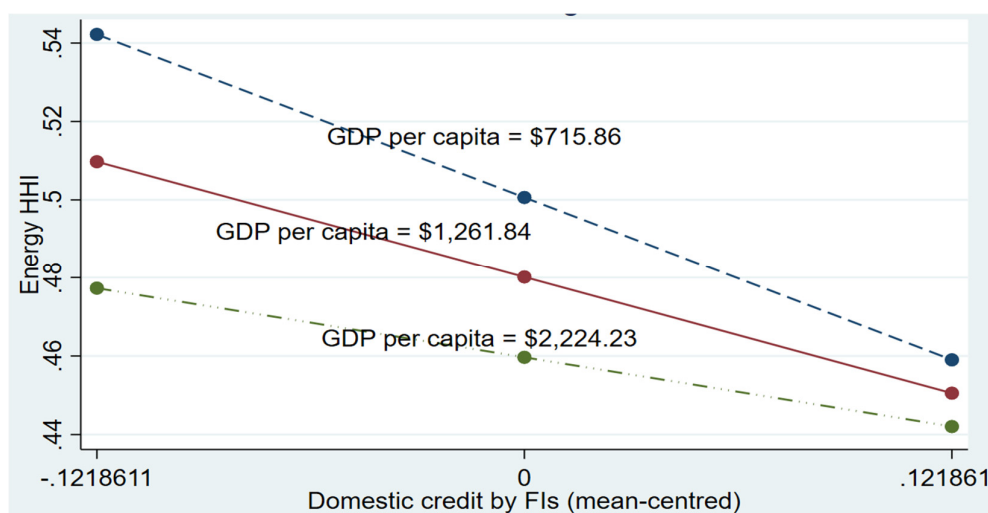
The results show that the coefficients on domestic credit and income are both negative and statistically significant. This indicates that, at the average income level, greater domestic credit is associated with lower energy concentration—implying a more diversified energy mix. Likewise, at the average level of domestic credit, higher-income countries tend to display greater diversification. These findings are consistent with the patterns documented earlier in Section 4.2.

The interaction between credit and income is positive and statistically significant, indicating that although credit continues to reduce energy concentration, the strength of this effect diminishes as income rises. This moderating pattern is evident in Figure 5, where the slopes representing the impact of domestic credit flatten across higher income levels. The predicted marginal effects in Table 12 reinforce this finding by showing that the beneficial effect of domestic credit is strongest at lower income levels and gradually weakens as GDP per capita increases, although it remains statistically significant throughout the observed income range. At low income (GDP per capita  $\approx$  USD 715), credit has a strong diversification effect ( $-0.0039^{***}$ ); at middle income ( $\approx$  USD 1262), the effect becomes weaker ( $-0.0024^{***}$ ); and at high income ( $\approx$  USD 2224), the effect is substantially smaller ( $-0.0010^{***}$ ). These results suggest that credit is most influential in low-income settings, where financial constraints are binding, but its marginal impact declines as countries advance economically, contrary to Hypothesis 4. A plausible explanation is that, in low-income settings, investment in renewable energy remains limited and firms often struggle to access financing for new technologies or infrastructure. When credit becomes more available, it is more likely to flow into these new or emerging energy sources, allowing the energy mix to broaden. As a result, the diversification effect of credit is more visible at early stages of development.

In higher-income economies in the sample, however, energy systems are already relatively diversified and capital markets are deeper, with a range of established financing options for clean energy projects. Additional domestic credit is therefore more likely to be used to upgrade or expand existing facilities rather than to reshape the overall structure of the energy mix, leading to a smaller marginal impact on diversification.

This interpretation is consistent with theories of technological and carbon lock-in. Arthur (1989) noted that systems are more flexible during their formative stages, allowing new investments to influence long-term trajectories. As incomes rise, energy infrastructures and institutions solidify around dominant technologies, making it harder for new financing to alter established patterns (Unruh, 2000). Seto et al. (2016) further showed that technological, institutional, infrastructural, and behavioral forms of lock-in

strengthen with development, causing mature energy systems to resist diversification. Together, these perspectives help explain why financial deepening encourages diversification most strongly in lower-income countries but has diminishing effects once energy systems are more firmly entrenched.



**Figure 5.** Marginal effects of domestic credit on energy concentration at selected levels of GDP per capita. Notes: Domestic credit and lnGDP per capita are one-year lagged and mean-centered. GDP per capita values are reported in levels (constant 2017 PPP-adjusted US dollars).

**Table 11.** Income effects on the domestic credit—Energy HHI link.

| Domestic Credit                 | Domestic Credit by FIs |                 |                 |                 |                 |                 | Domestic Credit by Banks |                 |                 |                 |                 |                 |
|---------------------------------|------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|--------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Models                          | (1)                    | (2)             | (3)             | (4)             | (5)             | (6)             | (7)                      | (8)             | (9)             | (10)            | (11)            | (12)            |
| <i>Trend</i>                    | −0.003***              | −0.003***       | −0.003***       | −0.004***       | −0.003***       | −0.003***       | −0.003***                | −0.003***       | −0.003***       | −0.004***       | −0.003***       | −0.003***       |
| <i>Dom Credit</i>               | −0.238***              | −0.230***       | −0.238***       | −0.239***       | −0.236***       | −0.236***       | −0.273***                | −0.254***       | −0.272***       | −0.268***       | −0.274***       | −0.273***       |
| <i>lnGDP pc</i>                 | −0.062***              | −0.067***       | −0.047***       | −0.040***       | −0.044***       | −0.061***       | −0.047***                | −0.053***       | −0.033***       | −0.027**        | −0.034**        | −0.048***       |
| <b><i>Dom credit</i></b>        | <b>*0.266***</b>       | <b>0.272***</b> | <b>0.255***</b> | <b>0.258***</b> | <b>0.256***</b> | <b>0.263***</b> | <b>0.300***</b>          | <b>0.303***</b> | <b>0.291***</b> | <b>0.292***</b> | <b>0.295***</b> | <b>0.300***</b> |
| <b><i>lnGDP pc</i></b>          |                        |                 |                 |                 |                 |                 |                          |                 |                 |                 |                 |                 |
| <i>LnOil Price</i>              | 0.017***               | 0.018***        | 0.014**         | 0.016***        | 0.014**         | 0.013**         | 0.018***                 | 0.019***        | 0.016***        | 0.017***        | 0.016***        | 0.015**         |
| <i>Capital Form</i>             | −0.104*                | −0.137*         | −0.106          | −0.105*         | −0.103*         | −0.100          | −0.077                   | −0.106          | −0.079          | −0.078          | −0.080          | −0.073          |
| <i>Edu Attain</i>               | 0.053*                 | 0.053**         | 0.045*          | 0.063*          | 0.045           | 0.041           | 0.049                    | 0.048*          | 0.041           | 0.059           | 0.040           | 0.037           |
| <i>CO<sub>2</sub> Emissions</i> | −0.002                 | −0.008          | 0.000           | 0.001           | −0.001          | 0.002           | −0.003                   | −0.009          | −0.001          | −0.000          | −0.002          | 0.002           |
| <i>Rule of Law</i>              | 0.041**                |                 |                 |                 |                 |                 | 0.040*                   |                 |                 |                 |                 |                 |
| <i>Corrupt Control</i>          |                        | 0.071***        |                 |                 |                 |                 |                          | 0.065***        |                 |                 |                 |                 |
| <i>Gov. Effective</i>           |                        |                 | 0.020           |                 |                 |                 |                          |                 | 0.019           |                 |                 |                 |
| <i>Voice &amp; Account</i>      |                        |                 |                 | 0.060**         |                 |                 |                          |                 |                 | 0.057**         |                 |                 |
| <i>Political Stability</i>      |                        |                 |                 |                 | 0.007           |                 |                          |                 |                 |                 | 0.010           |                 |
| <i>Reg Quality</i>              |                        |                 |                 |                 |                 | 0.052***        |                          |                 |                 |                 |                 | 0.053***        |
| <i>Constant</i>                 | 0.461***               | 0.463***        | 0.477***        | 0.469***        | 0.478***        | 0.472***        | 0.451***                 | 0.454***        | 0.465***        | 0.458***        | 0.463***        | 0.461***        |
| <i>Observations</i>             | 966                    | 966             | 966             | 966             | 966             | 966             | 966                      | 966             | 966             | 966             | 966             | 966             |

All explanatory and control variables, except the trend variable, are lagged by one year. Domestic credit and lnGDP per capita are mean-centered. \*\*\*, \*\*, and \* denote statistical significance at the 1%, 5%, and 10% levels, respectively.

**Table 12.** Marginal effects of domestic credit on energy concentration at selected levels of GDP per capita.

|                            | Marginal effect | t-statistic |
|----------------------------|-----------------|-------------|
| GDP per capita = \$715.86  | −0.3413***      | (−10.4340)  |
| GDP per capita = \$1261.84 | −0.2429***      | (−9.5085)   |
| GDP per capita = \$2224.23 | −0.1445***      | (−5.7323)   |

Notes: Domestic credit and GDP per capita are one-year lagged. GDP per capita values are expressed in levels (constant 2017 PPP-adjusted US dollars). \*\*\* denotes statistical significance at the 1% level.

#### 4.4. Robustness analysis using an alternative cardinal energy diversification measure

To examine whether the main findings depend on the measurement of energy diversification, we repeat the convergence and regression analyses using the cardinal energy diversification measure (*EnergyDIV*) proposed by Triguero-Ruiz et al. (2023). This measure is derived from the normalized energy HHI (*EnergyHHI*) presented in Equation (1) using the distance-to-balance framework developed by Triguero-Ruiz and Avila-Cano (2019):

$$EnergyDIV_{it} = 1 - \sqrt{EnergyHHI_{it}}. \quad (7)$$

The cardinal energy diversification measure ranges from 0 to 1, with higher values indicating greater energy diversification across energy sources. Unlike the normalized HHI, which measures energy concentration, the cardinal measure directly quantifies energy diversification while satisfying the cardinality property.

Table 13 reports the overall convergence results using the cardinal energy diversification measure. Consistent with the main analysis based on the normalized energy HHI, the  $\beta$ - and  $\sigma$ -convergence tests indicate convergence, whereas the Phillips and Sul log-t test rejects full-sample convergence. These results suggest that the main conclusion remains unchanged: countries do not converge toward a common steady state when the alternative diversification measure is adopted.

**Table 13.** Overall convergence tests using the cardinal energy diversification measure (*EnergyDIV*).

| Tests                           | $\beta$ test |         | $\sigma$ test |         | $\gamma$ test (log-t test) |         |
|---------------------------------|--------------|---------|---------------|---------|----------------------------|---------|
|                                 | Coef         | Std err | Coef          | Std err | Coef.                      | T-stat  |
| Cardinal energy diversification | −0.114***    | −0.015  | −0.118***     | −0.016  | −0.392                     | −12.808 |

$\beta$  and  $\sigma$  tests: \*\*\*: 1% level of significance, respectively; standard errors in parentheses.

$\gamma$  test: The null hypothesis of convergence is rejected at the 5% significance level if the t-statistic is below −1.65.

The club convergence analysis also confirms the existence of heterogeneous convergence patterns, although the composition of the convergence clubs differs from that obtained using the normalized energy HHI. Specifically, the cardinal energy diversification measure identifies two convergence clubs and one divergent group, compared with three convergence clubs and one divergent country under the normalized HHI. As shown in Appendix Tables A4–A5 and Figure A1, the countries forming the second convergence club and the divergent group under the cardinal measure are drawn exclusively from the first convergence club identified using the normalized energy HHI. In contrast, the first

convergence club under the cardinal measure combines all countries previously classified in the second and third convergence clubs under the normalized HHI together with the remaining countries from the original first convergence club. This indicates that the alternative diversification measure primarily changes the classification of countries in the high energy concentration club, while the overall conclusion of heterogeneous convergence remains unchanged.

Figure A1 further confirms the robustness of the convergence results using the alternative cardinal *EnergyDIV* index. Similar to the normalized energy HHI results, countries with more diversified initial energy structures remain on relatively higher diversification paths over time, whereas those with less diversified initial energy structures continue to follow lower diversification trajectories. These consistent patterns provide further support for path-dependent energy transitions and convergence toward distinct long-run equilibria rather than a common steady state.

Table 14 reports the regression results using the alternative cardinal energy diversification measure (*EnergyDIV*). Consistent with the results based on the normalized *EnergyHHI*, domestic credit remains positively and statistically significantly associated with energy diversification, the nonlinear relationship between GDP per capita and energy diversification is preserved, and the moderating effect of income on the domestic credit-energy diversification relationship remains statistically significant. Although the alternative cardinal energy diversification measure results in some differences in convergence club membership, the regression results remain qualitatively unchanged. Together, these findings demonstrate that the main conclusions are robust to adopting an alternative energy diversification measure that satisfies the cardinality property.

**Table 14.** Regression results using the alternative cardinal energy diversification measure (*EnergyDIV*).

| Domestic Credit                                          | <i>Domestic Credit by Fis</i> |          |          |           |          |          | <i>Domestic Credit by Banks</i> |           |          |           |          |           |
|----------------------------------------------------------|-------------------------------|----------|----------|-----------|----------|----------|---------------------------------|-----------|----------|-----------|----------|-----------|
| Models                                                   | G1                            | G2       | G3       | G4        | G5       | G6       | G1                              | G2        | G3       | G4        | G5       | G6        |
| <b>Part A: Baseline model (corresponding to Table 9)</b> |                               |          |          |           |          |          |                                 |           |          |           |          |           |
| <i>Trend</i>                                             | 0.002***                      | 0.002*** | 0.002*** | 0.003***  | 0.003*** | 0.002*** | 0.002***                        | 0.002***  | 0.002*** | 0.003***  | 0.002*** | 0.002***  |
| <i>Dom Credit</i>                                        | 0.093***                      | 0.087*** | 0.095*** | 0.096***  | 0.094*** | 0.093*** | 0.105***                        | 0.093***  | 0.107*** | 0.104***  | 0.106*** | 0.105***  |
| <i>lnGDP pc</i>                                          | 0.040***                      | 0.047*** | 0.035*** | 0.032***  | 0.030*** | 0.043*** | 0.037***                        | 0.044***  | 0.031*** | 0.029***  | 0.029*** | 0.040***  |
| <i>LnOil Price</i>                                       | -0.007*                       | -0.008*  | -0.006   | -0.008**  | -0.006   | -0.006   | -0.008**                        | -0.009**  | -0.007*  | -0.008**  | -0.007*  | -0.007    |
| <i>Capital Form</i>                                      | 0.099**                       | 0.119**  | 0.100**  | 0.102**   | 0.097**  | 0.097**  | 0.098**                         | 0.117**   | 0.099**  | 0.100**   | 0.098**  | 0.096**   |
| <i>Edu Attain</i>                                        | -0.039**                      | -0.040** | -0.035** | -0.048**  | -0.036** | -0.033** | -0.045**                        | -0.045*** | -0.041** | -0.053**  | -0.041** | -0.038**  |
| <i>CO<sub>2</sub> Emissions</i>                          | -0.005                        | -0.001   | -0.006   | -0.007    | -0.005   | -0.007   | -0.005                          | -0.001    | -0.006   | -0.007    | -0.005   | -0.008    |
| <i>Governance</i>                                        | -0.018                        | -0.041** | -0.011   | -0.042*** | -0.001   | -0.029** | -0.019                          | -0.040**  | -0.012   | -0.041*** | -0.003   | -0.031*** |
| <i>G1–G6</i>                                             |                               |          |          |           |          |          |                                 |           |          |           |          |           |
| <i>Constant</i>                                          | -0.021                        | -0.090   | 0.015    | 0.017     | 0.053    | -0.054   | 0.006                           | -0.059    | 0.045    | 0.051     | 0.068    | -0.027    |
| <i>Observations</i>                                      | 966                           | 966      | 966      | 966       | 966      | 966      | 966                             | 966       | 966      | 966       | 966      | 966       |

*Continued on next page*

| Domestic<br>Credit<br>Models                                                 | Domestic Credit by Fis |           |           |           |           |           | Domestic Credit by Banks |           |           |           |           |           |
|------------------------------------------------------------------------------|------------------------|-----------|-----------|-----------|-----------|-----------|--------------------------|-----------|-----------|-----------|-----------|-----------|
|                                                                              | G1                     | G2        | G3        | G4        | G5        | G6        | G1                       | G2        | G3        | G4        | G5        | G6        |
| <b>Panel B. Nonlinear income model (corresponding to Table 10)</b>           |                        |           |           |           |           |           |                          |           |           |           |           |           |
| <i>Trend</i>                                                                 | 0.002***               | 0.002***  | 0.003***  | 0.003***  | 0.003***  | 0.002***  | 0.002***                 | 0.002***  | 0.002***  | 0.003***  | 0.003***  | 0.002***  |
| <i>Dom Credit</i>                                                            | 0.104***               | 0.097***  | 0.105***  | 0.105***  | 0.104***  | 0.102***  | 0.125***                 | 0.111***  | 0.124***  | 0.121***  | 0.123***  | 0.124***  |
| <i>lnGDP pc</i>                                                              | 0.501***               | 0.515***  | 0.439**   | 0.448**   | 0.433**   | 0.481**   | 0.530***                 | 0.531***  | 0.461**   | 0.467**   | 0.456**   | 0.508**   |
| <i>(lnGDP pc)<sup>2</sup></i>                                                | -0.033**               | -0.033**  | -0.029**  | -0.030**  | -0.029**  | -0.031**  | -0.035***                | -0.035*** | -0.031**  | -0.032**  | -0.031**  | -0.034**  |
| <i>LnOil Price</i>                                                           | -0.008**               | -0.009**  | -0.007    | -0.008**  | -0.006    | -0.006    | -0.009**                 | -0.010**  | -0.007*   | -0.008**  | -0.007*   | -0.007    |
| <i>Capital Form</i>                                                          | 0.078                  | 0.100*    | 0.081     | 0.081     | 0.077     | 0.076     | 0.076                    | 0.097*    | 0.079     | 0.079     | 0.076     | 0.074     |
| <i>Edu Attain</i>                                                            | -0.040**               | -0.040**  | -0.034**  | -0.048**  | -0.035**  | -0.032*   | -0.046**                 | -0.046*** | -0.041**  | -0.054**  | -0.041**  | -0.038**  |
| <i>CO<sub>2</sub> Emissions</i>                                              | -0.013                 | -0.009    | -0.013    | -0.014    | -0.012    | -0.015    | -0.015                   | -0.010    | -0.015    | -0.016    | -0.014    | -0.018    |
| <i>Governance</i>                                                            | -0.026**               | -0.047*** | -0.011    | -0.043*** | -0.000    | -0.033*** | -0.028**                 | -0.046*** | -0.012    | -0.042*** | -0.003    | -0.036*** |
| <i>G1–G6</i>                                                                 |                        |           |           |           |           |           |                          |           |           |           |           |           |
| <i>Constant</i>                                                              | -1.621***              | -1.707*** | -1.371**  | -1.409**  | -1.325*   | -1.567**  | -1.703***                | -1.735*** | -1.425**  | -1.449**  | -1.387**  | -1.639**  |
| <i>Observations</i>                                                          | 966                    | 966       | 966       | 966       | 966       | 966       | 966                      | 966       | 966       | 966       | 966       | 966       |
| <b>Part C: Panel C. Income interaction model (corresponding to Table 11)</b> |                        |           |           |           |           |           |                          |           |           |           |           |           |
| <i>Trend</i>                                                                 | 0.002***               | 0.002***  | 0.002***  | 0.003***  | 0.003***  | 0.002***  | 0.002***                 | 0.002***  | 0.002***  | 0.003***  | 0.002***  | 0.002***  |
| <i>Dom Credit</i>                                                            | 0.156***               | 0.150***  | 0.156***  | 0.157***  | 0.155***  | 0.155***  | 0.193***                 | 0.180***  | 0.192***  | 0.189***  | 0.194***  | 0.193***  |
| <i>lnGDP pc</i>                                                              | 0.040***               | 0.045***  | 0.030**   | 0.025***  | 0.028***  | 0.040***  | 0.028**                  | 0.033***  | 0.018**   | 0.014*    | 0.019*    | 0.028***  |
| <i>Dom Credit</i>                                                            | *-0.179***             | -0.184*** | -0.172*** | -0.174*** | -0.173*** | -0.178*** | -0.213***                | -0.215*** | -0.207*** | -0.208*** | -0.209*** | -0.213*** |
| <i>lnGDP pc</i>                                                              |                        |           |           |           |           |           |                          |           |           |           |           |           |
| <i>LnOil Price</i>                                                           | -0.010**               | -0.011**  | -0.009*   | -0.010**  | -0.009*   | -0.008    | -0.011**                 | -0.012**  | -0.010**  | -0.011**  | -0.010**  | -0.009*   |
| <i>Capital Form</i>                                                          | 0.093*                 | 0.116**   | 0.094*    | 0.094**   | 0.092**   | 0.090*    | 0.074                    | 0.095*    | 0.076     | 0.075     | 0.076*    | 0.071     |
| <i>Educ Attain</i>                                                           | -0.039*                | -0.039**  | -0.033*   | -0.047*   | -0.033*   | -0.030*   | -0.035                   | -0.034*   | -0.030    | -0.043*   | -0.029    | -0.027    |
| <i>CO<sub>2</sub> Emissions</i>                                              | -0.003                 | 0.002     | -0.004    | -0.005    | -0.003    | -0.006    | -0.003                   | 0.001     | -0.005    | -0.005    | -0.004    | -0.007    |
| <i>Governance</i>                                                            | -0.028**               | -0.051*** | -0.014    | -0.044**  | -0.005    | -0.036*** | -0.028**                 | -0.047*** | -0.014    | -0.042**  | -0.007    | -0.038*** |
| <i>G1–G6</i>                                                                 |                        |           |           |           |           |           |                          |           |           |           |           |           |
| <i>Constant</i>                                                              | 0.315***               | 0.297***  | 0.315***  | 0.301***  | 0.321***  | 0.303***  | 0.324***                 | 0.307***  | 0.325***  | 0.311***  | 0.330***  | 0.311***  |
| <i>Observations</i>                                                          | 966                    | 966       | 966       | 966       | 966       | 966       | 966                      | 966       | 966       | 966       | 966       | 966       |

All explanatory and control variables, except the trend variable, are lagged by one year. G1 = Rule of Law; G2 = Control of Corruption; G3 = Government Effectiveness; G4 = Voice and Accountability; G5 = Political Stability; G6 = Regulatory Quality. For Part B: Domestic credit and lnGDP per capita are mean-centered. \*\*\*, \*\*, and \* denote statistical significance at the 1%, 5%, and 10% levels, respectively.

## 5. Conclusions and policy implications

This paper examines the long-run dynamics of energy diversification in 46 L/LMICs, with particular attention to the roles of domestic credit and income levels. Applying the Phillips-Sul convergence framework to energy concentration as the inverse measure of diversification, the analysis finds clear evidence against full-sample convergence, despite overall progress in energy diversification and a narrowing of cross-country disparities. Instead, countries sort into three distinct convergence clubs, indicating that energy diversification follows heterogeneous trajectories shaped by initial conditions rather than a single common transition path. The identified convergence clubs differ both in their initial degree of diversification and in their subsequent evolution. Countries that start with relatively diversified energy structures continue to broaden their energy mix over time, whereas those

with highly concentrated systems experience slower and more limited diversification. This pattern underscores the importance of initial energy structures and suggests that differences in diversification tend to persist over time rather than diminish.

The regression results further highlight the role of financial development in supporting energy diversification. Higher levels of domestic credit—measured through both financial institutions and banks—are consistently associated with lower energy concentration, implying a more diversified energy mix. The relationship between income per capita and energy diversification is nonlinear. Diversification initially increases with income but declines beyond an estimated turning point of approximately PPP\$2203. Because approximately 76% of the country-year observations lie below this threshold, higher income is associated with greater energy diversification for most observations in the sample. Importantly, the interaction analysis reveals that the diversification effect of domestic credit is income-dependent. Specifically, the beneficial effect of domestic credit on energy diversification is stronger at lower income levels and gradually weakens as income rises. This pattern indicates diminishing marginal returns to financial development in promoting energy diversification as economies become more developed.

The findings are robust to the choice of energy diversification measure. Whether diversification is measured using the normalized energy HHI or the alternative cardinal energy diversification index, the evidence consistently supports club convergence rather than convergence to a common steady state, while the estimated effects of domestic credit and income remain qualitatively unchanged.

The results of this study carry several implications for energy and financial policy in L/LMICs. A first implication concerns the design of energy diversification strategies. The identification of distinct convergence clubs indicates that countries enter the diversification process with different initial energy structures and follow different adjustment paths over time. This suggests that uniform energy transition strategies are unlikely to be effective across all countries. Economies with highly concentrated energy systems may require longer time horizons and sustained policy support—such as concessional finance, risk-sharing mechanisms, and transitional planning—to broaden their energy mix, whereas countries that already display relatively diversified structures can focus on consolidating and deepening diversification. Accounting for these differences can help policymakers set realistic targets and avoid overly ambitious timelines that are misaligned with structural conditions.

Second, the findings point to the importance of domestic credit availability in supporting energy diversification, particularly at lower income levels. In poorer economies, limited access to finance appears to be a key constraint on investment in alternative energy sources that are difficult to undertake due to high upfront costs and long payback periods. Policies that expand access to long-term and affordable financing for energy projects—particularly through development banks and credit guarantee schemes that provide long-term capital and reduce investment risk—are therefore likely to yield substantial diversification gains in low-income settings.

Third, the results indicate that the contribution of credit to diversification changes as economies develop. While domestic credit continues to support diversification at higher income levels, its marginal impact declines. This suggests that, in more advanced L/LMICs, further credit expansion alone is unlikely to deliver substantial diversification gains. Policy attention may therefore need to shift toward how financial resources are allocated, rather than how much credit is supplied. Greater coordination between energy planning and financial decision-making can help ensure that available financing supports energy investments consistent with diversification objectives.

Finally, the persistence of differences in diversification paths across countries implies that financial development, although important, is not sufficient on its own to ensure rapid energy diversification. Credit can ease investment constraints, but its effectiveness depends on the broader policy environment in which energy investments take place. For energy-sector stakeholders, this underscores the importance of stable and credible policy signals in shaping long-term investment decisions.

Overall, the findings suggest that effective energy diversification requires a staged and context-sensitive approach, in which financial policies evolve alongside income levels and existing energy structures. Aligning financial conditions with realistic energy transition pathways is likely to be central to achieving sustained diversification outcomes in developing economies.

### **Author contributions**

Thanh Nguyen: Conceptualization, methodology, data curation, formal analysis, software, visualization, and writing – original draft.

Eric Tham: Validation and writing – review and editing.

Both authors reviewed and approved the final manuscript.

### **Use of AI tools declaration**

The authors used generative AI tools exclusively for language editing purposes (e.g., clarity, grammar, and style), consistent with emerging guidance on responsible AI use in research (Dogru et al., 2026). All substantive content, analyses, and interpretations were developed by the authors.

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### **Conflict of interest**

The authors declare no conflict of interest.

### **Data availability statement**

Data in support of the findings of this study is available from the corresponding author upon reasonable request.

### **References**

- Achuo E, Kakeu P, Asongu S (2024) Financial development, human capital and energy transition: a global comparative analysis. *Int J Energy Sect Manag* 19: 59–80. <https://doi.org/10.1108/ijesm-11-2023-0004>.
- Afonso Ó, Fonseca L, Magalhães M, et al. (2020) Directed technical change and environmental quality. *Port Econ J* 20: 71–97. <https://doi.org/10.1007/s10258-020-00174-4>

- Ağazade S (2026) Is there a global trend toward better energy structure? Convergence analysis of energy diversification. *Int J Green Energy* 23: 504–513. <https://doi.org/10.1080/15435075.2025.2561202>
- Ahmad M, Uddin I (2025) Enhancing energy efficiency in OECD economies: The role of eco-friendly technology, financial development, and clean energy investment. *Sustain Futures* 10: 101258. <https://doi.org/10.1016/j.sftr.2025.101258>
- Akrofi MM (2020) An analysis of energy diversification and transition trends in Africa. *Int J Energy Water Resour* 5: 1–12. <https://doi.org/10.1007/s42108-020-00101-5>
- Alharbi SS, Boubaker S, Ngo T, et al. (2025) Shadow economy and energy efficiency: utilising goal programming for sustainability assessment. *Ann Oper Res*, 1–25. <https://doi.org/10.1007/s10479-025-06768-5>
- Alsagr N (2023) Financial efficiency and its impact on renewable energy investment: Empirical evidence from advanced and emerging economies. *J Clean Prod* 401: 136738. <https://doi.org/10.1016/j.jclepro.2023.136738>
- Anton SG, Afloarei Nucu AE (2020) The effect of financial development on renewable energy consumption. A panel data approach. *Renew Energy* 147: 330–338. <https://doi.org/10.1016/j.renene.2019.09.005>
- Arthur WB (1989) Competing Technologies, Increasing Returns, and Lock-In by Historical Events. *Econ J* 99: 116–131. <https://doi.org/10.2307/2234208>
- Aydin M, Bozatlı O (2023) The effects of green innovation, environmental taxes, and financial development on renewable energy consumption in OECD countries. *Energy* 280: 128105. <https://doi.org/10.1016/j.energy.2023.128105>
- Babayomi OO, Dahoro DA, Zhang Z (2022) Affordable clean energy transition in developing countries: Pathways and technologies. *iScience* 25: 104178. <https://doi.org/10.1016/j.isci.2022.104178>
- Barro RJ, Sala-i-Martin X (1992) Convergence. *J Polit Econ* 100: 223–251. <https://doi.org/10.1086/261816>
- Baumol WJ (1986) Productivity growth, convergence, and welfare: what the long-run data show. *Am Econ Rev*, 1072–1085.
- Baz K, Cheng J, Xu D, et al. (2021) Asymmetric impact of fossil fuel and renewable energy consumption on economic growth: A nonlinear technique. *Energy* 226: 120357. <https://doi.org/10.1016/j.energy.2021.120357>
- Beck T, Levine R, Loayza N (2000) Finance and the Sources of Growth. *J Financ Econ* 58: 261–300. [https://doi.org/10.1016/S0304-405X\(00\)00072-6](https://doi.org/10.1016/S0304-405X(00)00072-6)
- Bello AA, Agabo T, Adedoyin FF (2021) The anthropogenic consequences of energy consumption in Sub-Saharan Africa: Is there a role for education? *Environ Chall* 5: 100234. <https://doi.org/10.1016/j.envc.2021.100234>
- Bernard AB, Durlauf SN (1995) Convergence in international output. *J Appl Econom* 10: 97–108. <https://doi.org/10.1002/jae.3950100202>
- Bernard AB, Durlauf SN (1996) Interpreting tests of the convergence hypothesis. *J Econom* 71: 161–173. [https://doi.org/10.1016/0304-4076\(94\)01699-2](https://doi.org/10.1016/0304-4076(94)01699-2)
- Boubaker S, Le TDQ, Manita R, et al. (2025) The trade-off frontier for ESG and Sharpe ratio: a bootstrapped double-frontier data envelopment analysis. *Ann Oper Res* 347: 717–741. <https://doi.org/10.1007/s10479-023-05506-z>

- Calcaterra M, Aleluia Reis L, Fragkos P, et al. (2024) Reducing the cost of capital to finance the energy transition in developing countries. *Nat Energy* 9: 1241–1251. <https://doi.org/10.1038/s41560-024-01606-7>
- Campiglio E (2016) Beyond carbon pricing: The role of banking and monetary policy in financing the transition to a low-carbon economy. *Ecol Econ* 121: 220–230. <https://doi.org/10.1016/j.ecolecon.2015.03.020>
- Cheng J, Jiang Y (2024) How can carbon markets drive the development of renewable energy sector? Empirical evidence from China. *Data Sci Financ Econ* 4: 249. <https://doi.org/10.3934/DSFE.2024010>
- Diallo S, Ouoba Y (2024) Financial development and renewable energy deployment in sub-Saharan African countries. *Int J Energy Sect Manag* 18: 1305–1327. <https://doi.org/10.1108/IJESM-06-2023-0012>
- Dogan E, Chishti MZ, Karimi Alavijeh N, et al. (2022) The roles of technology and Kyoto Protocol in energy transition towards COP26 targets: Evidence from the novel GMM-PVAR approach for G-7 countries. *Technol Forecast Soc Change* 181: 121756. <https://doi.org/10.1016/j.techfore.2022.121756>
- Dogru T, Assaf A, Josiassen A, et al. (2026) Operationalizing GenAI: a framework protocol for auditable and responsible GenAI use in academic research. *Int J Contemp Hosp Manage* 38: 791–806. <https://doi.org/10.1108/IJCHM-06-2025-0837>
- Eren BM, Taspinar N, Gokmenoglu KK (2019) The impact of financial development and economic growth on renewable energy consumption: Empirical analysis of India. *Sci Total Environ* 663: 189–197. <https://doi.org/10.1016/j.scitotenv.2019.01.323>
- Gozgor G, Paramati SR (2022) Does energy diversification cause an economic slowdown? Evidence from a newly constructed energy diversification index. *Energy Econ* 109: 105970. <https://doi.org/10.1016/j.eneco.2022.105970>
- Gyimah J, Yao X, Tachega MA, et al. (2022) Renewable energy consumption and economic growth: New evidence from Ghana. *Energy* 248: 123559. <https://doi.org/10.1016/j.energy.2022.123559>
- Habiba U, Xinbang C, Anwar A (2022) Do green technology innovations, financial development, and renewable energy use help to curb carbon emissions? *Renew Energy* 193: 1082–1093. <https://doi.org/10.1016/j.renene.2022.05.084>
- Hajko V, Seabri M, Al-Saidi M, et al. (2018) The energy-growth nexus: history, development, and new challenges. *Econ Econom Energy-Growth Nexus*, 1–46. <https://doi.org/10.1016/B978-0-12-812746-9.00001-8>
- Hosier RH, Dowd J (1987) Household fuel choice in Zimbabwe: an empirical test of the energy ladder hypothesis. *Resour Energy* 9: 347–361. [https://doi.org/10.1016/0165-0572\(87\)90003-X](https://doi.org/10.1016/0165-0572(87)90003-X)
- Iqbal Z, Noor M (2023) The impact of energy consumption on economic growth in selected emerging economies. *J Energy Environ Policy Options* 6: 29–35.
- Islam MM, Ali MI, Ceh B, et al. (2022) Renewable and non-renewable energy consumption driven sustainable development in ASEAN countries: do financial development and institutional quality matter? *Environ Sci Pollut Res Int* 29: 34231–34247. <https://doi.org/10.1007/s11356-021-18488-x>
- Karanfil F, Omgba LD (2023) The energy transition and export diversification in oil-dependent countries: The role of structural factors. *Ecol Econ* 204: 107681. <https://doi.org/10.1016/j.ecolecon.2022.107681>

- Kor S, Qamruzzaman M (2023) Nexus between FDI, financial development, capital formation and renewable energy consumption: evidence from Bangladesh. *Int J Energy Econ Policy* 13: 129–145. <https://doi.org/10.32479/ijeep.14863>
- Kuziboev B, Ozturk I, Kalandarov F, et al. (2025) Promoting energy sources diversification through ESG performance. *Energy* 324: 136009. <https://doi.org/10.1016/j.energy.2025.136009>
- Le T-H, Nguyen CP, Park D (2020) Financing renewable energy development: Insights from 55 countries. *Energy Res Soc Sci* 68: 101537. <https://doi.org/10.1016/j.erss.2020.101537>
- Levine R (1997) Financial development and economic growth: views and agenda. *J Econ Lit* 35: 688–726.
- Levine R (2005) Finance and growth: theory and evidence. *Handbook Econ Growth* 1: 865–934. [https://doi.org/10.1016/S1574-0684\(05\)01012-9](https://doi.org/10.1016/S1574-0684(05)01012-9)
- Li B (2023) The role of financial markets in the energy transition: an analysis of investment trends and opportunities in renewable energy and clean technology. *Environ Sci Pollut Res Int* 30: 97948–97964. <https://doi.org/10.1007/s11356-023-29014-6>
- Li Y, Yang X, Ran Q, et al. (2021) Energy structure, digital economy, and carbon emissions: evidence from China. *Environ Sci Pollut Res Int* 28: 64606–64629. <https://doi.org/10.1007/s11356-021-15304-4>
- Limi FB (2020) Effect of financial development on energy diversification in Sub-Saharan Africa. *J. Energy Res Rev* 4: 29–38. <https://doi.org/10.9734/jenrr/2020/v4i330129>
- Liu W, Shen Y, Razzaq A (2023) How renewable energy investment, environmental regulations, and financial development derive renewable energy transition: Evidence from G7 countries. *Renew Energy* 206: 1188–1197. <https://doi.org/10.1016/j.renene.2023.02.017>
- Ma X, Mao Q (2025) Can Financial Development Promote Renewable Energy Transition? An Empirical Research Based on Global Panel Data. *Sustainability* 17: 9270. <https://doi.org/10.3390/su17209270>
- Mahdavi P, Martinez-Alvarez CB, Ross ML (2022) Why do governments tax or subsidize fossil fuels? *J Polit* 84: 2123–2139. <https://doi.org/10.1086/719272>
- Masera OR, Saatkamp BD, Kammen DM (2000) From linear fuel switching to multiple cooking strategies: a critique and alternative to the energy ladder model. *World Dev* 28: 2083–2103. [https://doi.org/10.1016/S0305-750X\(00\)00076-0](https://doi.org/10.1016/S0305-750X(00)00076-0)
- Mukhtarov S, Yüksel S, Dinçer H (2022) The impact of financial development on renewable energy consumption: Evidence from Turkey. *Renew Energy* 187: 169–176. <https://doi.org/10.1016/j.renene.2022.01.061>
- Murshed M, Tanha MM (2021) Oil price shocks and renewable energy transition: Empirical evidence from net oil-importing South Asian economies. *Energy Ecol Environ* 6: 183–203. <https://doi.org/10.1007/s40974-020-00168-0>
- Nawaz A, Rahman MM (2023) Renewable energy consumption in Sub-Saharan Africa: The role of human capital, foreign direct investment, financial development, and institutional quality. *Energy Rep* 10: 3383–3393. <https://doi.org/10.1016/j.egyr.2023.10.025>
- Nchofoung TN (2024) Oil price shocks and energy transition in Africa. *Energy Policy* 184: 113855. <https://doi.org/10.1016/j.enpol.2023.113855>
- Nguyen T, Nghiem S, Doan A-T (2025) Energy diversification, financial development and economic development: an examination of convergence in OECD countries. *China Financ Rev Int* 15: 337–362. <https://doi.org/10.1108/CFRI-07-2024-0427>

- Nibedita B, Irfan M (2024) Energy mix diversification in emerging economies: An econometric analysis of determinants. *Renew Sustain Energy Rev* 189: 114043. <https://doi.org/10.1016/j.rser.2023.114043>
- Olaniyi CO, Al-Faryan MAS, Ogbaro EO (2025) Do institutional quality and its threshold matter in the sensitivity of the renewable energy transition to financial development? New empirical perspectives. *Int J Financ Econ* 30: 5–43. <https://doi.org/10.1002/ijfe.2900>
- Oluoch S, Lal P, Susaeta A (2021) Investigating factors affecting renewable energy consumption: A panel data analysis in Sub Saharan Africa. *Environ Chall* 4: 100092. <https://doi.org/10.1016/j.envc.2021.100092>
- Ozturk I (2010) A literature survey on energy–growth nexus. *Energy Policy* 38: 340–349. <https://doi.org/10.1016/j.enpol.2009.09.024>
- Pablo-Romero MdP, Sánchez-Braza A, Sánchez-Rivas J (2024) A survey of energy-environmental Kuznets curve studies, *Handbook on Energy and Economic Growth*, 173–198, Edward Elgar Publishing. <https://doi.org/10.4337/9781802204803.00016>
- Pasandideh AS, Ezaan G (2025) Governance challenges of renewable energy development in fossil fuel dependent countries with a focus on Iran. *Energy Sustain Dev* 87: 101759. <https://doi.org/10.1016/j.esd.2025.101759>
- Pata UK, Alola AA, Erdogan S, et al. (2023) The influence of income, economic policy uncertainty, geopolitical risk, and urbanization on renewable energy investments in G7 countries. *Energy Econ* 128: 107172. <https://doi.org/10.1016/j.eneco.2023.107172>
- Payne JE, Saunoris JW, Nazlioglu S, et al. (2024) Renewable energy production across US states: Convergence or divergence? *Energy Econ* 140: 108015. <https://doi.org/10.1016/j.eneco.2024.108015>
- Phillips PCB, Sul D (2007) Transition modeling and econometric convergence tests. *Econometrica* 75: 1771–1855. <https://doi.org/10.1111/j.1468-0262.2007.00811.x>
- Phillips PCB, Sul D (2009) Economic transition and growth. *J Appl Econom* 24: 1153–1185. <https://doi.org/10.1002/jae.1080>
- Pinar M (2024) Convergence in renewable energy innovation and factors influencing convergence club formation. *Renew Energy* 220: 119607. <https://doi.org/10.1016/j.renene.2023.119607>
- Polzin F, Egli F, Steffen B, et al. (2019) How do policies mobilize private finance for renewable energy?—A systematic review with an investor perspective. *Appl Energy* 236: 1249–1268. <https://doi.org/10.1016/j.apenergy.2018.11.098>
- Presno MJ, Landajo M (2021) EU-28’s progress toward the 2020 renewable energy share: A club convergence analysis. *Environ Sci Pollut Res* 28: 66830–66844. <https://doi.org/10.1007/s11356-021-15084-x>
- Raifu IA, Nnadozie OO, Adeniyi OA (2021) Infrastructure-structural transformation nexus in Africa: the role of financial sector development. *J Afr Dev* 22: 124–165. <https://doi.org/10.5325/jafrideve.22.1.0124>
- Ranis G, Fei JCH (1961) A theory of economic development. *Am Econ Rev* 533–565.
- Rubio-Varas M, Munoz-Delgado B (2019) The Energy Mix Concentration Index (EMCI): Methodological considerations for implementation. *MethodsX* 6: 1228–1237. <https://doi.org/10.1016/j.mex.2019.05.023>

- Saadaoui H, Chtourou N (2023) Do institutional quality, financial development, and economic growth improve renewable energy transition? Some evidence from Tunisia. *J Knowl Econ* 14: 2927–2958. <https://doi.org/10.1007/s13132-022-00999-8>
- Saba CS, Ngepah N (2022a) Convergence in renewable energy sources and the dynamics of their determinants: An insight from a club clustering algorithm. *Energy Rep* 8: 3483–3506. <https://doi.org/10.1016/j.egyr.2022.01.190>
- Saba CS, Ngepah N (2022b) Convergence in renewable energy consumption and their influencing factors across regions: evidence from convergence algorithm approach. *Environ Sci Pollut Res Int* 29: 61412–61445. <https://doi.org/10.1007/s11356-022-19731-9>
- Seto KC, Davis SJ, Mitchell RB, et al. (2016) Carbon lock-in: types, causes, and policy implications. *Annu Rev Environ Resour* 41: 425–452. <https://doi.org/10.1146/annurev-environ-110615-085934>
- Shahbaz M, Siddiqui A, Ahmad S, et al. (2023) Financial development as a new determinant of energy diversification: the role of natural capital and structural changes in Australia. *Energy Econ* 126: 106926. <https://doi.org/10.1016/j.eneco.2023.106926>
- Solarin SA, Bello MO, Hammoudeh S (2024) Transiting toward sustainable development: stochastic convergence of energy diversification using a newly constructed index. *Environ Sci Pollut Res Int* 31: 47611–47629. <https://doi.org/10.1007/s11356-024-34341-3>
- Tiba S, Omri A (2017) Literature survey on the relationships between energy, environment and economic growth. *Renew Sustain Energy Rev* 69: 1129–1146. <https://doi.org/10.1016/j.rser.2016.09.113>
- Triguero-Ruiz F, Avila-Cano A, Aranda FT (2023) Measuring the diversification of energy sources: The energy mix. *Renew Energy* 216: 119096. <https://doi.org/10.1016/j.renene.2023.119096>
- Triguero-Ruiz F, Avila-Cano A, Trujillo Aranda F (2025) The role of energy diversification in the average income and pollution intensity of OECD economies. *Energy Sources Part B Econ Plan Policy* 20: 2588260. <https://doi.org/10.1080/15567249.2025.2588260>
- Triguero-Ruiz F, Avila-Cano A (2019) The distance to competitive balance: A cardinal measure. *Appl Econ* 51: 698–710. <https://doi.org/10.1080/00036846.2018.1512743>
- Tzeremes P (2024) Sectoral Convergence Trends in per Capita Energy Use Among US States. *Stud Microecon*, 23210222241275739. <https://doi.org/10.1177/23210222241275739>
- Unruh GC (2000) Understanding carbon lock-in. *Energy Policy* 28: 817–830. [https://doi.org/10.1016/S0301-4215\(00\)00070-7](https://doi.org/10.1016/S0301-4215(00)00070-7)
- Vatamanu AF, Zugravu BG (2023) Financial development, institutional quality and renewable energy consumption. A panel data approach. *Econ Anal Policy* 78: 765–775. <https://doi.org/10.1016/j.eap.2023.04.015>
- Wang Q, Dong Z (2021) Does financial development promote renewable energy? Evidence of G20 economies. *Environ Sci Pollut Res Int* 28: 64461–64474. <https://doi.org/10.1007/s11356-021-15597-5>
- Zafar MW, Shahbaz M, Hou F, et al. (2019) From nonrenewable to renewable energy and its impact on economic growth: The role of research & development expenditures in Asia-Pacific Economic Cooperation countries. *J Clean Prod* 212: 1166–1178. <https://doi.org/10.1016/j.jclepro.2018.12.081>

