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Research article

Can international financial assistance drive the clean energy transition in developing countries?

Manh-Tien Bui[1] and Thai-Ha Le[2,*]

[1] Crawford School of Public Policy, the Australian National University, Australia
[2] VinUniversity & VinFuture Foundation, Hanoi, Vietnam; IPAG Business School, Paris, France

* **Correspondence:** Email: v.md@vinfutureprize.org, thai1@e.ntu.edu.sg.

Abstract: In this study, we investigated the role of international financial assistance in promoting clean energy development and environmental sustainability across 89 developing countries from 2000 to 2021. Using a Panel ARDL model with the Pooled Mean Group (PMG) estimator, assesses assessed the short- and long-run effects of global financial flows directed toward clean energy research, development, and production (RD&P). The findings revealed that while international financial assistance contributes to reductions in CO_2 emissions in the long run, its influence on the renewable energy share in total energy supply remains weak and statistically insignificant. This outcome reflects the structural challenges facing developing economies, particularly rapid energy demand growth driven by industrialization and limited absorptive capacity for green technologies. The results further highlight the critical role of governance quality in shaping the effectiveness of external finance: Stronger governance systematically amplifies environmental returns in upper-income economies while influencing the relationship differently in lower-income settings. Policy implications suggest that international support should not only increase in scale but also be better targeted and better governed, emphasizing system-enabling investments, institutional strengthening, and long-term policy alignment to ensure a sustained and inclusive clean-energy transition.

Keywords: international financial assistance; renewable energy; developing countries; energy transition; environmental impacts

JEL: F30, O13, Q56

1. Introduction

Attaining net-zero emissions requires a fundamental technological and structural transformation of the global energy system, extending beyond incremental improvements in energy efficiency to encompass deep decarbonization through clean energy innovation, research and development (R&D), and large-scale deployment of renewable energy (RE) technologies. Such transformation is indispensable for achieving the goals of the Paris Agreement and Sustainable Development Goal 7 (SDG 7) on affordable and clean energy (IEA, 2023; IPCC, 2022). However, developing economies face severe constraints in financing this transition due to limited fiscal capacity, shallow domestic capital markets, and high country-risk premiums that deter private investors (Songwe et al., 2020; World Bank, 2023).

As a result, these economies rely heavily on international financial channels, including grants, concessional loans, blended-finance instruments, foreign direct investment (FDI), and official development assistance (ODA), to fund clean-energy R&D and RE production (UNEP, 2016; OECD, 2021). These financial flows not only bridge the investment gap but also enable technology transfer, capacity building, and policy learning, helping developing countries adopt low-carbon technologies more rapidly (Altenburg & Rodrik, 2017).

Despite growing commitments, the global financing landscape remains skewed. According to the International Energy Agency (IEA, 2021), more than two-thirds of total CO_2 emissions originate from emerging markets and developing economies (EMDEs), whereas emissions in advanced economies are steadily declining. This asymmetry highlights the urgency and the opportunity for a global collaborative effort to accelerate renewable energy investment in the developing world. The United Nations Conference on Trade and Development (UNCTAD, 2023) estimates that while the annual RE investment requirement in EMDEs is around US $1.7 trillion, actual green FDI inflows reached only US $544 billion in 2022.

Beyond private investment, public international assistance plays a critical complementary role. UNSTAT (2023) reports that international grants, loans, and equity investments to support RE research, development, and production (RD&P) in developing countries exceeded US $12 billion in 2020. Nonetheless, the effectiveness of these financial flows in catalyzing the energy transition and improving environmental quality remains empirically uncertain (Buntaine & Pizer, 2015).

Moreover, the impact of international finance depends critically on domestic governance quality and institutional readiness, which determine whether external resources are translated into effective renewable capacity and sustained environmental benefits (Dollar & Kraay, 2003; Hallegatte & Rozenberg, 2017). Weak institutions, policy uncertainty, and low absorption capacity often blunt the effectiveness of aid, leading to project fragmentation or delayed implementation.

Although researchers have explored the environmental implications of FDI and renewable energy investment (Fadly, 2019; Haldar & Sethi, 2021; Shahbaz et al., 2020), relatively few have examined the role of international financial assistance targeted at clean energy RD&P. Moreover, research tends to aggregate diverse financial instruments, i.e., grants, ODA, and private capital, without distinguishing their technological or institutional dimensions. This leaves open critical questions about whether and how such assistance contributes to the energy transition and emissions reduction in developing economies.

To address this gap, we investigate the question:

Can international financial assistance in clean energy effectively stimulate the green transition and reduce CO_2 emissions in developing countries?

Using a panel dataset covering 89 countries from 2000 to 2021, the analysis employs a Panel ARDL approach with the PMG estimator to capture both short- and long-run dynamics. The results reveal that while international financial assistance has a modest but statistically significant long-run effect in reducing CO_2 emissions, its impact on the renewable share of total energy supply remains weak. This suggests that international finance contributes more to environmental improvement than to structural transformation of the energy mix. Additionally, the results indicate the importance of governance quality, as countries with stronger institutions are more successful in converting financial inflows into tangible renewable energy capacity and emission reductions.

These findings have important policy implications. They suggest that global climate finance mechanisms, such as the Green Climate Fund (GCF) and Just Energy Transition Partnerships (JETP), should not only scale up financial resources but also strengthen governance-linked conditionalities, enhance transparency, and promote system-enabling investments (e.g., grids, storage, and innovation ecosystems). In doing so, international financial assistance can better serve as a catalyst for low-carbon growth and a foundation for a just, inclusive, and sustainable energy transition in the developing world.

This study contributes to the literature in several ways. First, unlike much of the research that aggregates climate finance or foreign investment flows, we focus on international financial assistance directed toward clean energy research, development, and production (RD&P), measured through the SDG 7.a.1 indicator. This distinction enables us to isolate the effects of targeted clean-energy financial assistance rather than broader financial flows.

Second, we distinguish two key dimensions of the energy transition: environmental outcomes (CO_2 emissions reduction) and structural transformation of the energy system (changes in the renewable energy share). These two outcomes may respond differently to international finance, as financial assistance can reduce emissions through technology diffusion, efficiency improvements, and cleaner energy substitution before large-scale structural changes in the energy mix occur.

Third, we propose a conceptual framework in which international financial assistance influences the clean energy transition through four major channels: Easing capital constraints for renewable investments, facilitating technology transfer and learning, reducing project risks and crowding in private investment, and strengthening institutional and policy capacity in recipient countries. These mechanisms operate over different time horizons and institutional contexts, motivating the dynamic panel approach adopted in this study.

The remainder of this paper is structured as follows: In Section 2, we review the related literature. In Section 3, we outline the empirical strategy, including the baseline model specification, data sources, and econometric techniques, employed to examine the nexus between international financial assistance, renewable energy adoption, and environmental performance. In Section 4, we present and discuss the empirical results, highlighting long- and short-run dynamics across income groups and institutional contexts. In Section 5, we conclude the paper by summarizing the key findings and their implications for policy design and global climate finance mechanisms aimed at supporting a just and effective clean-energy transition in developing countries.

2. Literature review

International public finance is theorized to accelerate the energy transition in developing countries through four reinforcing channels: (i) Easing capital constraints on renewables and grids; (ii) transferring technology and know-how through tied technical assistance and procurement; (iii) derisking projects to crowd in private capital; and (iv) nudging institutional upgrading via policy dialogue and conditionality. Evidence from the innovation literature shows that clean technologies generate larger positive knowledge spillovers than "dirty" ones, implying higher social returns to directing finance toward clean research, development, and deployment (Dechezleprêtre et al., 2017). This mechanism is particularly relevant for emerging and developing economies with weak domestic innovation systems.

A first strand examines whether climate- or energy-tagged aid raises clean investment and reduces emissions. Buntaine and Pizer (2015) provide an early and influential assessment showing that aid explicitly targeted to clean energy can promote investment, but its effectiveness depends on the design of assistance and the recipient's policy environment. Their findings highlight the importance of institutional capacity and governance quality, foreshadowing the heterogeneity observed across income groups and governance levels in later studies.

A second strand focuses on the scale and composition of international public flows. Tracking of SDG indicator 7.a.1 shows that international public financial flows to developing countries in support of clean-energy research, development, and deployment rebounded to about USD 15.4 billion in 2022, approximately 25% higher than in 2021, yet only half the 2016 peak, highlighting that concessional finance remains well below what is needed, especially for least-developed and lower-income economies (UN Statistics Division, 2024). These data also reveal persistent provider-reporting gaps and classification differences, which create attenuation risk in macro-panel econometrics and help explain the small coefficients often found for financial-flow variables. Complementary evidence from multilateral development banks (MDBs) shows record climate finance in 2024 (USD 137 billion), roughly two-thirds of which was for mitigation and the bulk directed to low- and middle-income countries (African Development Bank [AfDB], 2025; Inter-American Development Bank [IDB], 2025; Reuters, 2025a). While MDB totals are broader than SDG 7.a.1, as they include adaptation and private co-financing, they signal the growing availability of blended capital that can catalyze private flows.

A third strand evaluates renewable-energy–emissions elasticities and why results differ by context. Cross-country analyses consistently find that raising the renewable share reduces CO_2 emissions, but the magnitude depends on the fossil mix displaced, grid integration, and concurrent demand growth. Recent global tracking reports highlight record renewable additions yet caution that deployment lags the rate needed to meet 2030 targets, particularly in emerging markets where electricity demand is rising rapidly (Reuters, 2025b). This pattern helps rationalize findings such as large negative long-run elasticities of emissions with respect to the renewable share coupled with difficulty increasing that share meaningfully amid rapid total-energy growth.

A fourth strand addresses foreign direct investment (FDI) and technology transfer, which are relevant because concessional finance often aims to crowd in private capital rather than substitute for it. Early empirical work shows that FDI can reduce energy intensity in developing countries through technology and managerial spillovers (Hübler & Keller, 2010), while newer studies emphasize that technology-oriented international investment is more effective when domestic policy frameworks are credible and reduce regulatory risk. For identification, this suggests that the standalone coefficient on public finance likely understates the total effect in contexts where crowd-in occurs, and may appear insignificant where institutional credibility is weak.

Across these strands, two moderators repeatedly emerge. Governance and institutions play a central role: Stronger institutional quality enhances the absorptive capacity for external finance by improving project selection, procurement, and permitting, thereby amplifying environmental gains

(Saba et al., 2025). Conversely, weak governance can delay implementation and dilute benefits, which is consistent with results showing that governance supports emissions reductions overall but has muted or negative effects on the renewable share in low-income settings. Project-cycle timing and composition also matter. Some life-cycle assessments indicate that although operational emissions of renewable energy technologies are very low, upstream phases such as materials extraction, manufacturing, transportation and installation can contribute non-negligible emissions. Once the asset is commissioned and begins operation, the net emission benefits usually accrue over the long run (Jain and Bardhan, 2024; Sobczuk et al., 2025). Composition is equally important: Finance directed toward grids, storage, and flexibility yields outsized long-run payoffs by enabling higher renewable penetration, whereas flows to general infrastructure without clean-energy conditionality may raise emissions temporarily.

Research highlights that the effectiveness of environmental policies and climate-related financial flows is strongly conditioned by institutional quality and governance structures. Empirical studies increasingly show that governance dimensions such as regulatory quality, corruption control, and the rule of law significantly affect how financial and policy interventions translate into environmental outcomes (e.g., Azimi et al., 2023; Saba et al., 2025). In particular, corruption control has been shown to influence the structure of energy consumption by shaping the allocation of public resources and the credibility of regulatory frameworks supporting renewable energy development (Xu, 2025). This institutional perspective is especially important in developing countries, where weak governance, fragmented regulation, and limited administrative capacity can reduce the effectiveness of clean-energy policies and delay the implementation of renewable energy investments.

A related strand of literature further shows that these governance constraints are closely intertwined with the size of the informal or shadow economy. Evidence from developing countries indicates that weak governance enables informal economic activity to expand, thereby worsening environmental degradation and undermining the effectiveness of sustainability policies; by contrast, stronger governance can mitigate these adverse effects by improving regulatory enforcement and reducing pollution-intensive informal activities (Si et al., 2025; Wang et al., 2024). This suggests that the environmental returns to international financial assistance depend not only on the scale of external resources, but also on the ability of recipient countries to channel those resources through effective and credible institutions.

More broadly, empirical work reinforces the argument that environmental performance and energy-transition outcomes are shaped by the interaction between policy frameworks, institutional capacity, and structural energy choices. Comparative evidence across major country groups shows that renewable-energy strategies are associated with improvements in environmental outcomes, although their effectiveness varies with broader economic and institutional conditions (Cristea et al., 2022). Similarly, studies highlight that financial development, governance quality, and technological change jointly influence the pace and direction of energy transition processes, particularly in emerging and developing economies (Xu et al., 2024). Taken together, this literature supports the view that international finance alone is insufficient to deliver a sustained clean-energy transition unless it is accompanied by governance reforms, stronger implementation capacity, and more coherent regulatory environments.

Finally, emerging sustainability research highlights the broader links between energy transition, resource efficiency, and the circular economy. Clean-energy investments can generate wider systemic benefits when combined with policies that promote efficient resource use, low-carbon industrial processes, and sustainable production systems. In this sense, international climate finance may contribute not only to emissions reduction but also to broader sustainability transformations when embedded within coherent policy and governance frameworks.

Methodologically, multi-country work favors estimators that separate short- and long-run dynamics and accommodate cross-sectional dependence, such as PMG versions of the autoregressive distributed-lag (ARDL) model with robust errors (UN Statistics Division, 2024). This reflects the globally co-moving shocks, including fuel prices and technology costs, that characterize energy data. The panel-ARDL PMG approach with Driscoll–Kraay robustness used in this study therefore aligns with current best practice.

In synthesis, the literature suggests that international public finance can help developing countries transition to greener energy, but its impacts are conditional on where (governance capacity), what (RD&D, grid, flexibility versus general infrastructure), and when (construction versus operation). Combined with evidence on the limited scale of current finance (UN Statistics Division, 2024; UNCTAD, 2023), this implies two policy levers for stronger effectiveness: (i) Better targeting of finance toward system-enabling investments and innovation with high social spillovers; and (ii) institutional reforms that enhance absorption and crowd-in, which are consistent with the empirical findings of this paper.

3. Methodology and data

3.1. Baseline model

To empirically examine the role of international financial assistance in promoting the clean energy transition and environmental sustainability, we adopt a baseline panel specification of the following form:

$$\mathrm{Y_{it}} = \alpha_0 + \alpha_1 \mathrm{finp_{it}} + \sum_{k=2}^{n} \alpha_k \mathrm{Controls_{it}} + \rho_i + \varepsilon_{it} \quad [1]$$

where Y_{it} represents indicators of the green transition for country i in year t. Two dependent variables are used: (i) The renewable energy supply ratio ($rsup$), which is the share of renewable energy in total energy supply capturing the energy transition; and (ii) CO_2 emissions per capita ($emip$, in logarithmic form) that reflect environmental outcomes.

The key explanatory variable, $finp$, measures per capita international financial flows supporting clean energy research, development, and production (RD&P); this includes grants, concessional loans, credits, and equity investments directed to developing countries under *SDG Indicator 7.a.1*.[1] While

[1] It should be noted that the SDG 7.a.1 dataset aggregates several forms of international financial assistance into a single indicator of financial flows supporting clean energy RD&P. While this aggregated measure enables consistent cross-country comparison, it does not permit disaggregation by financial instrument. Different financing instruments may generate heterogeneous impacts on energy transition outcomes. For example, grants may support early-stage innovation and institutional capacity building, while concessional loans and blended finance mechanisms may facilitate large-scale infrastructure investments. Because the SDG dataset does not consistently report these components separately, we focus on the overall effect of international financial assistance. In future studies. researchers could explore the differential impacts of financing instruments using project-level climate finance datasets.

international finance theoretically operates through capital, technological, risk, and institutional channels, the aggregate nature of SDG Indicator 7.a.1 captures the net macroeconomic effect of these combined mechanisms rather than isolating their individual contributions.

Other control variables include GDP per capita ($gdpp$), capturing income-driven energy demand and scale effects; energy intensity (eni), representing energy efficiency (ktoe per million USD of GDP); and governance quality (gov), proxied by the *control of corruption index*, to account for institutional effectiveness.[2] This measure is particularly relevant in the context of energy-transition finance because corruption control affects the transparency, credibility, and allocative efficiency of public institutions involved in energy investment and project implementation. Evidence from ASEAN countries shows that stronger corruption control is significantly associated with the structure of energy consumption, including renewable and non-renewable energy use, which supports the use of this indicator as a meaningful proxy for governance quality in energy-transition analysis (Xu, 2025).

In the CO_2 emission model, $rsup$ is included as an additional control to assess whether renewable energy penetration mediates the emission effect. Except for $rsup$ and governance, all variables are expressed in natural logarithms (e.g., $lfinp$, $lgdpp$, and $leni$) to stabilize variance and interpret coefficients as elasticities. The term ρ_i captures unobserved country-specific effects, and ε_{it} is the idiosyncratic error term.

Although governance quality is included as a control variable in the baseline specification, its role may extend beyond a direct effect to a moderating influence on the effectiveness of international financial assistance. In particular, stronger institutional frameworks may enhance countries' capacity to translate external financial resources into effective renewable energy deployment and emissions reductions. To capture this mechanism more explicitly, we estimate an extended specification that includes an interaction term between international financial assistance and governance quality ($lfinp \times gov$), enabling us to examine how institutional quality shapes the effectiveness of climate finance.

3.2 Data

We employ an unbalanced panel dataset covering 89 countries, comprising 48 low- and lower-middle-income and 41 upper-middle- and high-income economies, over the period 2000–2021. The dataset integrates multiple international sources to capture the interplay between economic development, governance, renewable energy transition, and environmental outcomes.

Carbon dioxide emissions per capita (*emip*), measured in kilograms and later transformed into logarithmic form (*lemip*), are obtained from the International Energy Agency (IEA) and serve as the primary environmental indicator. The key explanatory variable, renewable energy supply ratio (*rsup*),

[2] Although the Control of Corruption Index is used as the primary governance indicator in the baseline model, governance quality is inherently multidimensional and includes aspects such as regulatory quality, rule of law, and government effectiveness. These indicators are often highly correlated in cross-country datasets, and including multiple governance measures simultaneously may generate multicollinearity issues. The control of corruption indicator is therefore selected as a parsimonious proxy capturing institutional integrity and transparency in public resource allocation; factors particularly relevant for the effective implementation of externally financed infrastructure projects. Nevertheless, this choice represents a limitation of the analysis, as it may not fully capture the complexity of institutional environments across countries. Future research could extend the analysis by incorporating broader institutional indices or composite governance measures to examine how different institutional dimensions influence the effectiveness of climate finance.

represents the share of renewable energy in total primary energy supply, also sourced from the IEA. Economic development is proxied by GDP per capita (*gdpp*) in constant 2017 PPP-adjusted US dollars from the World Development Indicators (WDI), with its logarithmic form (*lgdpp*) used in the regressions.

Energy efficiency is represented by energy intensity (*eni*), the ratio of total energy supply to GDP (ktoe per million US dollars), sourced from the IEA and WDI, and later expressed in logarithmic form (*leni*). Financial support for clean energy innovation is captured by international financial flows for clean energy R&D (*finp*), measured in 2020 US dollars and normalized by population to obtain per capita values (converted to logarithmic form, *lfinp*), collected from UNSTAT's SDG Indicator 7.a.1 database. Institutional quality is proxied by the control of corruption index (gov) from the Worldwide Governance Indicators (WGI), reflecting perceptions of the extent to which public power is exercised for private gain.

Descriptive statistics for all variables are presented in Table 1. On average, countries in the sample record 2,490 kg of CO_2 emissions per capita, with renewable energy accounting for 38.9% of total energy supply. The mean GDP per capita is US$9,339 (PPP, 2017 constant), and energy intensity averages 0.141 ktoe per million US$ of GDP. International clean energy financial inflows average US$4.81 per capita, though with substantial variation across countries and years. Governance quality is generally low, averaging –0.58, consistent with the dominance of developing economies in the sample.

All variables are subjected to standard transformations and diagnostic checks before estimation, ensuring comparability and robustness across income groups and over time.

Table 1. Descriptive statistics.

Variable	Definition & Calculation	Unit	Obs	Mean	Std. Dev.	Min	Max
emip	CO2 Emission per capita (taken logarithm later - *lemip*)	kg	1869	2490.453	2686.769	29.732	15663.864
rsup	Ratio of renewable energy supply in total energy supply	-	1869	0.389	0.33	0	1.771
gdpp	Gross domestic product divided by population (taken logarithm later - *lgdpp*)	2017 US$ PPP	1869	9339.515	6780.119	628.693	35688.648
eni	Energy intensity, total energy supply divided by GDP (taken logarithm later – *leni*)	ktoe/ million US$	1869	0.141	0.098	0.023	0.778
finp	International financial flows to developing countries in support of clean energy research and development (convert to per capita and taken logarithm later – *lfinp*)	2020 US$	1869	4.807	20.16	0	507.368
gov	Governance quality index, proxied by control of corruption, which is defined as "… perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests."	-	1869	−0.579	0.579	−1.673	1.544

Note: Energy data is collected from International Energy Agency, population and gross domestic data is collected from World Development Indicators (World Bank), control of corruption index is collected from Worldwide Governance Indicators (World Bank), and international finance flows data is collected from UNSTAT (SDG indicator 7.a.1). Source: Authors' calculations.

3.3 Empirical approach

Given the dynamic nature of energy transitions and possible heterogeneity across economies, we employ the Panel Autoregressive Distributed Lag (ARDL) framework, estimated via the Pooled Mean Group (PMG) estimator (Pesaran et al., 1999). This approach distinguishes short-run fluctuations from long-run equilibrium relationships and enables slope heterogeneity in short-run dynamics while constraining long-run coefficients to be homogeneous across countries.

Prior to estimation, the dataset is tested for multicollinearity, cross-sectional dependence, unit roots, cointegration, and slope heterogeneity (Tables 2 and 3). The results indicate no serious multicollinearity but confirm the presence of cross-sectional dependence, reflecting globally linked energy and financial markets, and mixed stationarity across levels. The presence of cointegration, confirmed by Kao (1999), Pedroni (1999), and Westerlund (2005) tests, justifies the ARDL approach.

Table 2. Cross-sectional dependence (CD) and unit roots tests.

	CD test *CD test*	CIPS test *CIPS**	IPS test *Z-t-tilde-bar*	HT test *Rho (Z)*
Variables in levels				
lemip	87.841***	−2.094	1.3040	4.9281
rsup	35.982***	−2.102	0.5855	1.1356
lgdpp	195.952***	−1.556	−0.2567	4.6327
leni	81.841***	−2.221**	−0.4859	1.3036
lfinp	70.74***	−4.173**	−14.5176***	−35.6966***
gov	1.222	−1.583	−1.6575*	−2.3297**
Variables in first difference				
Δ*lemip*	29.593***	−3.917**	−17.4770***	−53.6840***
Δ*rsup*	10.117***	−4.175**	−19.4146***	−59.6315***
Δ*lgdpp*	98.779***	−2.925**	−5.6716***	−49.5152***
Δ*leni*	8.617***	−4.214**	−26.1092***	−61.8116***
Δ*lfin*	2.229*	−5.605**	−19.5673***	−84.1907***
Δ*gov*	3.729***	−3.933**	−20.1836***	−58.3261***

Notes: *, **, and *** denote significance at the 5%, 1%, and 0.1% levels, respectively. Δ is the first difference. CD test is cross-sectional dependence test following Pesaran (2021). Unit root tests are based on methods provided by Pesaran (2007), Im et al. (2003), and Harris and Tzavalis's (1999) subsequently.

Table 3. Multicolinearity, cointegration, and slope heterogeneity tests.

Multicolinearity test (VIF)			
rsup	lgdpp 1.46 / leni 1.37 / gov 1.22 / lfinp 1.09 / Mean VIF: 1.29		
lemip	lgdpp 2.83 / leni 1.46/ gov 1.22 / lfinp 1.09 / rsup 2.10 / Mean VIF: 1.74		
Cointegration tests			
	Kao *Dickey-Fuller t*	Pedroni *Phillips-Perron t*	Westerlund *Variance ratio*
rsup	2.2639**	-1.7717**	3.6535***
lemip	1.8758**	-5.1997***	1.8601**
Slope heterogeneity test			
	Delta	Adjusted Delta	
rsup	35.480***	41.980***	
lemip	20.740***	26.360***	

Note: *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. Cointegration tests follow the methods provided by Kao (1999), Pedroni (1999) and Westerlund (2005). Slope heterogeneity tests follow Bersvendsen and Ditzen (2021), while model selection between MG and PMG follows Hausman (1978).

Slope heterogeneity tests confirm the presence of significant parameter heterogeneity across countries, which is economically expected given the diversity of the 89-country sample in terms of industrialization stage, institutional development, and energy-system structure. This validates the use of heterogeneous estimators and rules out conventional pooled or fixed-effects approaches. To choose between the Mean Group (MG) estimator, which enables all coefficients to vary freely, and the Pooled Mean Group (PMG) estimator, which constrains long-run coefficients to be homogeneous while permitting short-run heterogeneity, we conduct Hausman (1978) tests under the null hypothesis that the PMG long-run homogeneity restriction is valid. The results fail to reject this null in both equations (*rsup*: $\chi^2 = 6.64$, p-value = 0.1562; *lemip*: $\chi^2 = 1.51$, p-value = 0.9117), indicating that the long-run restriction is statistically supported and that the PMG estimator is preferred over MG on efficiency and consistency grounds.

The unrestricted error correction model regression is:

$$\Delta Y_{it} = \theta_{1i} + \omega_{1i}.\left(Y_{i,t-1} - \gamma_{11}.lfinp_{i,t} - \sum_{k=2}^{n} \gamma_{1k}.Controls_{i,t}\right) + \sum_{j=1}^{a} \delta_{11ij}.\Delta Y_{i,t-j} + \sum_{k=2}^{n}\sum_{j=0}^{b} \delta_{1kij}.\Delta Controls_{i,t-j} + \tau_{1it} \quad [2]$$

with θ denoting the drift, ω is the error correction coefficient, indicating the speed at which short-run deviations adjust toward the long-run equilibrium, and γ and δ denoting the long-run and short-run coefficients, respectively. Parameters a and b are the optimal lag lengths for each variable, and τ is a white noise error term. The PMG estimator ensures efficiency and robustness in the presence of heterogeneous adjustment dynamics across countries.

A further methodological consideration concerns potential endogeneity, cross-sectional dependence, and serial autocorrelation in the panel. Regarding endogeneity, the Panel ARDL framework provides a degree of built-in mitigation through its dynamic lag structure; the error correction specification reduces, though does not eliminate, the risk of reverse causality bias arising from the contemporaneous correlation between international financial flows and energy outcomes (Pesaran et al., 1999). The more substantive threats to inference in this panel, however, are cross-sectional dependence and autocorrelation, which arise naturally from the globally co-moving shocks that simultaneously affect all countries in the sample. These issues are not resolved by alternative endogeneity-focused estimators such as System-GMM, which address simultaneity bias but do not account for cross-sectional error correlation (Sarafidis & Wansbeek, 2012). The robustness checks therefore apply Driscoll-Kraay (1998) standard errors to the baseline specification, as this estimator explicitly corrects for heteroskedasticity, autocorrelation, and cross-sectional dependence in panel data without requiring instrumental variables. The broad consistency between the PMG results and the Driscoll-Kraay estimates reinforces confidence in the results under these alternative error assumptions.

4. Results and discussion

4.1. Preliminary analysis

Figure 1 illustrates the evolution of key indicators, economic growth, energy supply, renewable energy development, and CO_2 emissions, across developing countries between 2000 and 2020. A clear and persistent link emerges between GDP growth, total energy supply, and CO_2 emissions, suggesting that economic expansion continues to be a principal driver of energy demand and environmental degradation. Periods of rapid output growth, notably in the early and mid-2000s, coincide with accelerated increases in total energy consumption and emissions, while downturns such as in 2009 and 2015–2016 show synchronized contractions across all three indicators. This pattern reveals the strong energy-growth-emission nexus in developing economies.

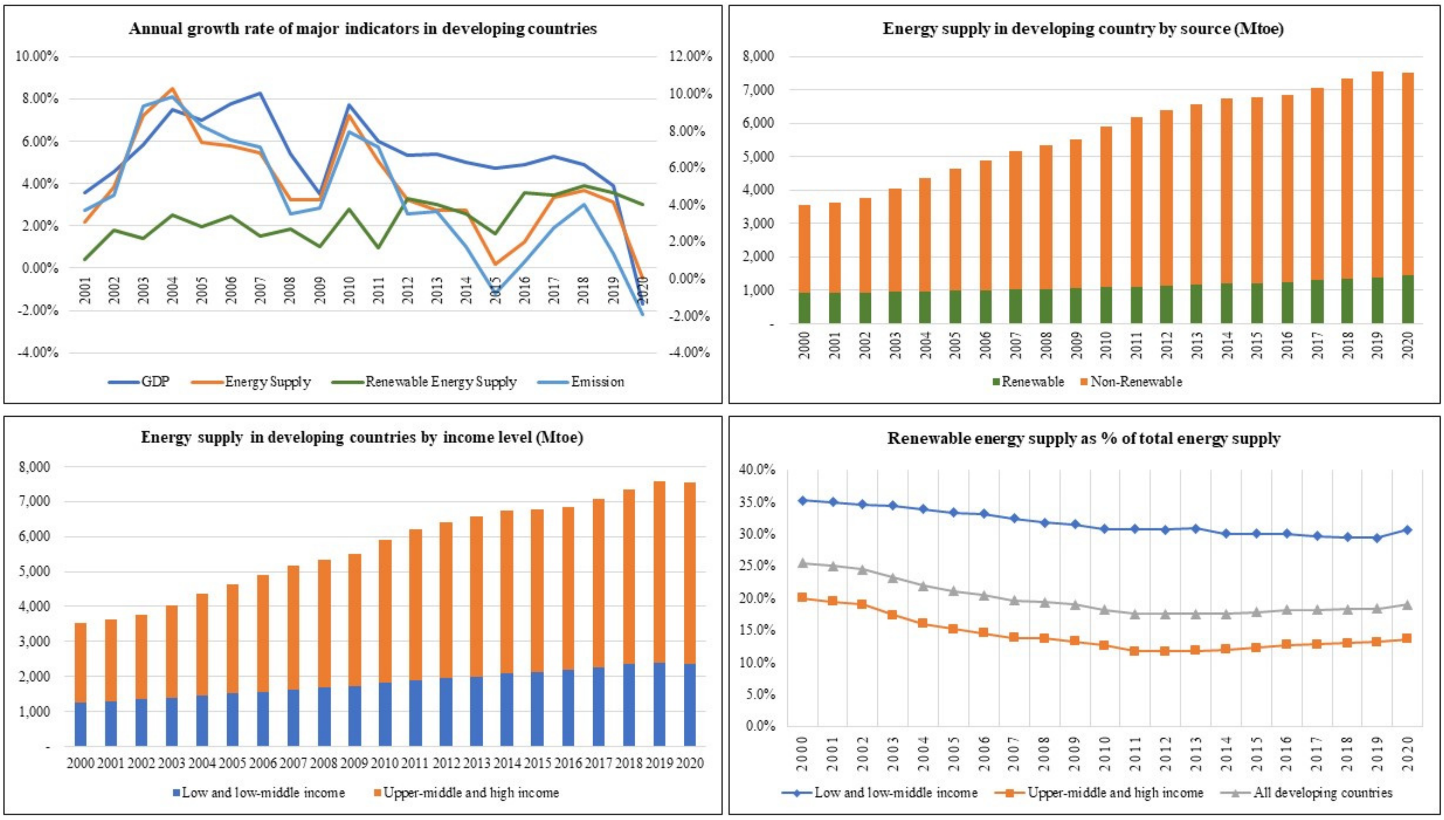

Figure 1. Major trends in energy supply, economies, and environment in developing countries.

Throughout the period, non-renewable energy sources overwhelmingly dominate the supply mix. Although renewable energy expands gradually in absolute terms, its share in total energy supply declines from around 2000 to 2011, before showing a mild recovery after 2012. This rebound corresponds to the period when the growth rate of renewable supply temporarily outpaces that of total energy supply, likely due to falling renewable technology costs, international commitments under the Paris Agreement, and the rise of climate finance initiatives. Nonetheless, the dominance of fossil fuels persists, and the renewable share remains insufficient to offset overall growth in energy demand.

The income-based disparities in energy structure are also pronounced. Upper-middle- and high-income developing countries account for most of the total energy consumption, with their energy supply expanding far more rapidly than that of low- and lower-middle-income economies; yet, the latter maintain a much higher proportion of renewables, approximately 30–35%, compared with 15–20% in wealthier developing peers. This gap reflects not only differences in industrial structure and technological capacity but also the continued reliance of lower-income countries on traditional renewables such as biomass and hydropower, while higher-income developing economies' industrialization remains heavily fossil-fuel-based.

Taken together, these trends reveal that despite the global momentum toward clean energy, developing countries remain locked in a growth-energy-emission cycle. Renewable energy deployment, while expanding, has not scaled sufficiently to alter the overall energy composition. This indicates the challenge of achieving an effective decoupling between economic growth and carbon emissions, a task that requires intensified international financial support and stronger domestic policy commitments to accelerate the transition toward sustainable energy systems.

Figure 2 presents the distribution of international financial flows supporting clean energy research, development, and production (RD&P) across developing countries by income level. A clear pattern emerges: A disproportionately large share of global clean energy funding is directed toward low- and lower-middle-income economies, while upper-middle- and high-income developing countries receive relatively smaller inflows. This concentration of aid in lower-income economies reflects the traditional focus of international assistance on developmental and capacity-building needs, where concessional finance, grants, and public-sector loans remain the dominant channels.

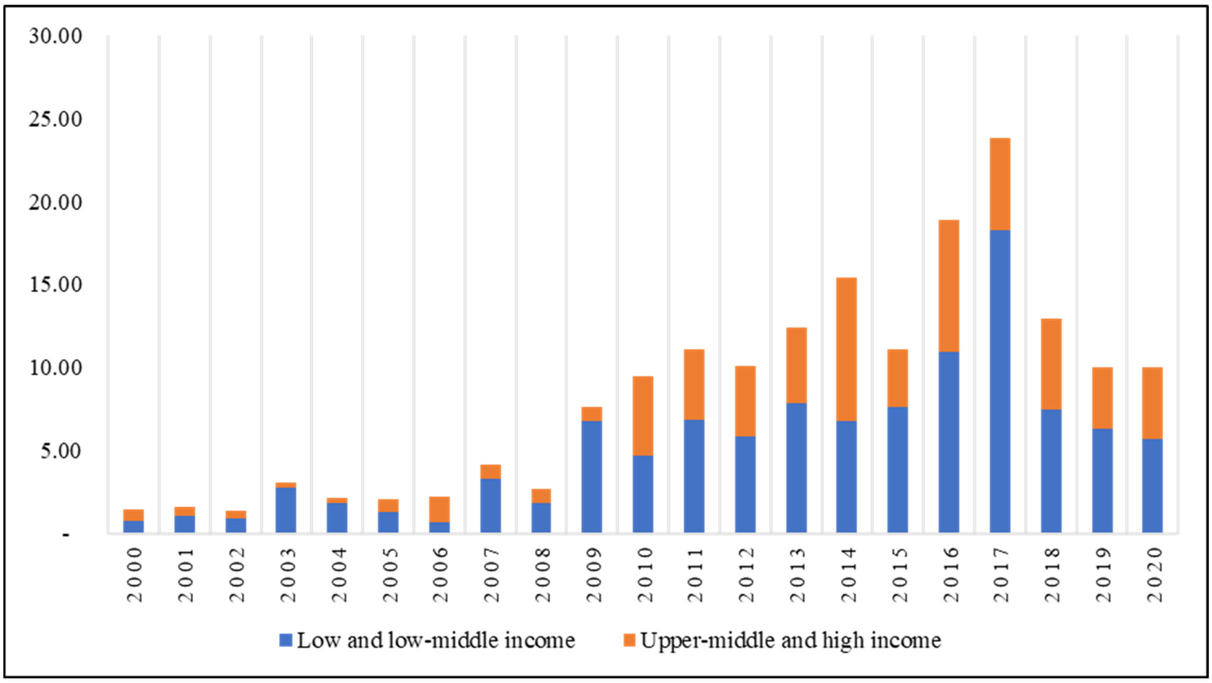

Figure 2. International finance for clean energy RD&P in developing countries by income level (US$ billion).

However, the volatility and uneven growth of these flows over time suggest that international clean energy finance remains episodic rather than structural, often responding to donor priorities or short-term global initiatives rather than sustained national energy strategies. The peaks observed in the late 2010s coincide with global climate finance mobilization following the Paris Agreement, while subsequent fluctuations indicate fragile financial commitments and project-level bottlenecks.

In contrast, upper-middle-income economies rely more heavily on private and blended investment mechanisms to support renewable energy development, reflecting stronger financial markets, higher creditworthiness, and access to global investors; yet, this also implies that concessional international support plays a complementary rather than catalytic role in these economies. Taken together, the figure highlights a persistent divide in the structure and stability of clean energy financing across income groups, implying the need for more predictable, coordinated, and performance-linked financial mechanisms to ensure that international funding translates effectively into long-term green energy transitions.

4.2. Empirical results

Table 4. Regression results.

	Full sample		Upper-middle and high income sample		Low and lower-middle income sample	
	rsup	lemip	rsup	lemip	rsup	lemip
Long-run estimations						
lgdpp	−0.0371***	0.8486***	−0.2249***	1.0559***	0.0012	0.6768***
	(0.0067)	(0.0200)	(0.0089)	(0.0213)	(0.0168)	(0.0420)
leni	−0.1312***	0.5770***	−0.1386***	0.8360***	0.0154	0.5917***
	(0.0085)	(0.0317)	(0.0123)	(0.0291)	(0.0167)	(0.0461)
lfinp	−0.0006***	−0.0038***	−0.0007**	−0.0036***	−0.0014***	−0.0026***
	(0.0002)	(0.0006)	(0.0003)	(0.0006)	(0.0003)	(0.0009)
gov	0.0120***	0.1183***	0.0054	0.0156	−0.0151**	0.1042***
	(0.0045)	(0.0128)	(0.0077)	(0.0137)	(0.0068)	(0.0203)
rsup		−1.9855***		−1.1824***		−2.4598***
		(0.0725)		(0.0826)		(0.1327)
Short-run estimations						
EC terms	−0.1223***	−0.2352***	−0.1230***	−0.3425***	−0.0929***	−0.2395***
	(0.0212)	(0.0302)	(0.0349)	(0.0473)	(0.0223)	(0.0389)
Δlgdpp	−0.1870***	0.8455***	−0.1003***	0.7100***	−0.2412***	0.9046***
	(0.0258)	(0.1063)	(0.0271)	(0.1244)	(0.0408)	(0.1849)
Δleni	−0.1505***	0.6233***	−0.0856***	0.5253***	−0.2144***	0.6514***
	(0.0276)	(0.0944)	(0.0317)	(0.1060)	(0.0419)	(0.1701)
Δlfinp	0.0001	0.0012**	0.0001	0.0012*	0.0002	0.0009
	(0.0001)	(0.0005)	(0.0001)	(0.0006)	(0.0002)	(0.0006)
Δgov	−0.0031	−0.0517***	−0.0028	−0.0245	0.0044	−0.0626**
	(0.0050)	(0.0164)	(0.0054)	(0.0172)	(0.0071)	(0.0261)
Δrsup		−0.2145		2.0606		−2.6334***
		(1.7712)		(2.7223)		(0.5540)
Constant	0.0475***	0.3866***	0.2492***	0.0412**	0.0511***	0.8109***
	(0.0100)	(0.0484)	(0.0690)	(0.0189)	(0.0149)	(0.1288)
Obs	1780	1780	820	820	960	960

Note: Standard errors are in parentheses; *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. Δ is the first difference. EC is the error correction terms.

Table 4 presents the long-run and short-run estimation results for the full sample, the upper-middle and high-income group, and the low- and lower-middle-income group. Table 5 extends these results with an interaction term between international financial flows and governance quality. Across all specifications, the short-run estimates show slower adjustment processes, as reflected in the statistically significant and negative error-correction (EC) terms, confirming convergence toward long-run equilibrium. For instance, the EC coefficient for the *lemip*-model regression (−0.235) indicates that about 23.5% of deviations from the long-run equilibrium are corrected each year. Overall, the findings confirm a strong and statistically significant relationship between renewable energy transition, international financial flows, governance quality, and CO_2 emissions across the full sample and the income-based subsamples. However, the magnitude and direction of these effects vary markedly between short- and long-run horizons and across income categories.

Table 5. Regression results with interaction term (lfinp×gov).

	Full sample		Upper-middle and high income sample		Low and lower-middle income sample	
	rsup	lemip	rsup	lemip	rsup	lemip
Long-run estimations						
lgdpp	−0.0271***	0.8889***	−0.0242***	0.9345***	0.0471*	1.1183***
	(0.0075)	(0.0174)	(0.0081)	(0.0209)	(0.0260)	(0.0482)
leni	−0.1262***	0.9347***	−0.1138***	0.9832***	−0.1766***	0.6756***
	(0.0090)	(0.0189)	(0.0112)	(0.0226)	(0.0136)	(0.0568)
lfinp	−0.0006***	−0.0032***	−0.0005*	−0.0027***	−0.0136***	−0.0063***
	(0.0002)	(0.0007)	(0.0003)	(0.0007)	(0.0018)	(0.0021)
gov	−0.0001	0.1017***	−0.0016	0.0949***	−0.1554***	−0.3348***
	(0.0050)	(0.0102)	(0.0061)	(0.0112)	(0.0259)	(0.0307)
rsup		−2.0127***		−1.8865***		−3.0414***
		(0.0519)		(0.0505)		(0.1522)
lfinp×gov	−0.0014***	−0.0029***	−0.0015***	−0.0026***	−0.0126***	0.0027
	(0.0004)	(0.0009)	(0.0006)	(0.0009)	(0.0018)	(0.0024)
Short-run estimations						
EC terms	−0.1185***	−0.2366***	−0.1516***	−0.2422***	−0.0867**	−0.1620***
	(0.0234)	(0.0378)	(0.0340)	(0.0780)	(0.0401)	(0.0362)
Δlgdpp	−0.1827***	0.8901***	−0.1125***	0.8001***	−0.2507***	0.8064***
	(0.0262)	(0.1067)	(0.0272)	(0.1093)	(0.0412)	(0.1713)
Δleni	−0.1494***	0.6183***	−0.0831**	0.5629***	−0.2055***	0.6464***
	(0.0279)	(0.1088)	(0.0325)	(0.1231)	(0.0421)	(0.1640)
Δlfinp	−0.0015	0.0068	−0.0040	0.0212	0.0013*	−0.0029
	(0.0021)	(0.0069)	(0.0043)	(0.0142)	(0.0007)	(0.0026)
Δgov	−0.0283	0.5046	−0.0549	1.1342	−0.0036	−0.0314
	(0.0224)	(0.5371)	(0.0449)	(1.0811)	(0.0152)	(0.0327)
Δrsup		1.6808		5.2335		−2.8680***
		(3.3609)		(5.8903)		(0.6683)
Δlfinp×gov	−0.0009	0.0384	−0.0027	0.0839	0.0010	−0.0027
	(0.0015)	(0.0380)	(0.0030)	(0.0764)	(0.0009)	(0.0040)
Constant	0.0386***	0.4974***	0.0257***	0.4096***	−0.0341**	−0.0125
	(0.0103)	(0.0813)	(0.0084)	(0.1422)	(0.0162)	(0.0321)
Obs	1780	1780	820	820	960	960

Note: Standard errors are in parentheses; *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. Δ is the first difference. EC is the error correction terms.

In the long run, the share of renewable energy supply (*rsup*) exhibits a strong, negative, and statistically significant effect on CO_2 emissions (*lemip*) across all groups. The elasticities range from roughly −1.182 in upper-middle and high-income countries to −2.460 in low and lower-middle income countries, suggesting that expanding renewable energy yields larger emission-reduction payoffs in the lower-income group. This result aligns with research indicating that the marginal impact of clean-energy deployment can be higher in contexts where fossil-fuel dependence is greater and the base renewable share lower (Jie and Rabnawaz, 2024).

In the short run, however, the effects of changes in renewable share on emissions are weaker and statistically insignificant in the full and upper-income samples. Only in the lower-income group are the short-run coefficients of *rsup* consistent with the long-run results. This suggests that in poorer countries, where traditional renewables such as biomass and hydropower account for 30−35% of supply (Figure 1), even short-run shifts in the energy mix generate immediate emissions effects. For higher-income developing economies, the transition benefits of renewable expansion are largely a long-run phenomenon.

Economic growth (*lgdpp*), by contrast, is positively associated with emissions in all samples, with coefficients ranging from 0.677 to 1.056 in the long run and 0.710 to 0.905 in the short run. Such findings indicate that growth in developing countries remains carbon-intensive despite structural improvements. Interestingly, the impact of economic growth on renewable energy supply shows a similar tendency, but in the opposite direction, across all sample groups in the short term, while it is positive but insignificant only for the low- and lower-middle-income group in the long term. This result suggests that growth-driven energy demand in developing countries often prioritizes output expansion over sustainability and therefore continues to favor non-renewable sources. This interpretation is supported by the coefficients of energy intensity (*leni*), which follow the opposite trajectory to economic growth *lgdpp* in the short and long run, reinforcing the energy-emission nexus: Higher energy inefficiency is a robust driver of carbon output while negatively affecting renewable energy uptake, since energy-intensive economies tend to rely on non-renewable, dispatchable power sources to meet continuous industrial demand. This is consistent with research arguing that technical inefficiency hampers clean-energy deployment (Adhikari, 2022).

Turning to international financial flows (*lfinp*), the results demonstrate small but statistically significant negative effects on renewable energy supply and emissions. Specifically, a 1% increase in clean energy finance per capita reduces CO_2 emissions by approximately 0.0038% in the full sample, indicating that long-term financial assistance promotes cleaner technologies and gradually contributes to emission reduction. This echoes earlier findings (Buntaine & Pizer, 2015) that clean-energy aid can reduce emissions, albeit with small effect sizes and conditional on institutional factors. In the short run, international financial flows (*Δlfinp*) have a positive but weak effect on CO_2 emissions (0.0012) while their influence on renewable energy supply is negligible and statistically insignificant. This finding may reflect the transitional phase of investment implementation, where infrastructure development, manufacturing, and installation of renewable facilities temporarily raise emissions before producing environmental gains.

The short-run increase in emissions associated with international financial inflows may reflect the life-cycle characteristics of renewable energy infrastructure. While renewable technologies generate minimal emissions during operation, the early stages of project development, including material extraction, equipment manufacturing, transportation, and installation, can generate temporary increases in carbon emissions. Life-cycle assessment studies have shown that these upstream emissions are typically offset over the operational lifespan of renewable facilities, resulting in substantial net emissions reductions over time (Jain and Bardhan, 2024; Sobczuk et al., 2025).

Therefore, the positive short-run coefficient observed in the model may reflect the transitional phase of renewable energy deployment, during which infrastructure construction temporarily increases emissions before long-term environmental benefits materialize. For example, the construction of large-scale solar parks or wind farms requires substantial amounts of steel, cement, and transportation infrastructure, all of which are associated with energy-intensive production processes. Similarly, hydropower projects often involve large civil engineering works that generate temporary emissions during construction. These infrastructure requirements may explain why international financial inflows supporting renewable deployment can coincide with short-run increases in emissions before the long-run environmental benefits emerge.

Although the estimated coefficient of international financial assistance on emissions appears small in magnitude, its interpretation should be considered in the context of the scale of national energy systems. For example, the estimated coefficient implies that a 10% increase in per capita international clean energy financial flows is associated with approximately a 0.038% reduction in CO_2 emissions in the long run. While modest, such effects accumulate over time and across countries, particularly when financial flows support infrastructure investments whose environmental benefits persist for decades. Moreover, international financial assistance typically represents only a small share of total energy investment in developing countries, implying that even modest estimated elasticities may correspond to meaningful environmental improvements when combined with domestic investment and policy reforms.

Governance quality (*gov*) emerges as another crucial determinant of environmental outcomes. It shows a positive long-run association with renewable energy supply in the full sample (0.012) but a negative one in low and lower-middle income countries (−0.015). This result echoes evidence that stronger corruption control improves the structure of energy consumption by supporting renewable energy use and reducing distortions in public resource allocation (Xu, 2025). However, this finding also provides the additional insight that the capacity of institutional quality to enhance the energy transition is highly context-dependent, primarily benefiting economies that already possess established regulatory frameworks. Moreover, *gov* positively affects emissions in the long run in the full sample (0.118) and the low-income sample (0.104), suggesting that better governance does not automatically guarantee improved long-term environmental outcomes. This paradoxical pattern is consistent with the dynamics discussed above: Governance improvements are associated with simultaneous increases in renewable energy capacity and overall emissions. This reflects the dual nature of institutional capacity in developing economies, where stronger governance accelerates broad economic activity, energy access expansion, and productive investment, including fossil-fuel-intensive industrialization, rather than directing capacity strictly toward environmental regulation.

In the short run, changes in governance (Δgov) reduce emissions in the full sample (–0.052) and the low-income subsample (−0.063) but have no significant short-run effect on the renewable share. This asymmetry - immediate emissions benefits without a short-run structural shift in the energy mix - is consistent with the notion that governance improvements can deliver rapid gains through regulatory enforcement and public investment prioritization, but cannot immediately overcome the capital and infrastructure barriers to renewable deployment. While stronger governance can help minimize environmental harm in the short term, governments in developing countries often revert to priorities of economic growth over the longer term.

The interaction term results in Table 5 reveal that the governance–finance relationship acts as a central moderating mechanism in the energy transition. The $lfinp \times gov$ coefficient is negative and statistically significant for renewable energy supply (*rsup*) across all income groups. This indicates that stronger governance dampens the marginal effect of international finance on the renewable energy share. Consistent with the earlier discussion, this suggests that more capable governments may prioritize reliable baseload generation and broader grid infrastructure to meet rapid industrial demand, rather than strictly focusing on variable renewable deployment in the long run.

However, the interaction term's coefficients for emissions (*lemip*) reveal a divergent environmental narrative. The interaction is negative and statistically significant only in the full sample and the upper-middle and high-income subsample. This indicates that in these more developed settings, stronger governance amplifies the emissions-reducing effect of international finance; every unit increase in governance quality raises the marginal environmental benefit of financial flows. Conversely, for low- and lower-middle-income countries, the interaction is positive and statistically insignificant. This implies that in low-income settings, while institutional quality may dictate how external finance is initially allocated, it is not sufficient to determine whether that finance translates into sustained emission reductions.

When comparing income groups, distinct patterns emerge. In upper-middle and high-income economies, the transition toward renewables is embedded in policy and market mechanisms, leading to a lower elasticity of emissions to renewable energy expansion (−1.182). In these settings, the primary constraint appears to be the scale and targeting of financial flows: Economic growth actively crowds out the renewable energy share (−0.225), while governance amplifies the emissions-reducing effect of finance through a complementary finance–governance interaction (−0.0026). Furthermore, the faster error correction rate for emissions in these economies (−0.343) reflects more responsive institutional and market mechanisms.

In low- and lower-middle-income countries, however, the long-run coefficient of −2.460 indicates a much stronger potential payoff from renewable energy adoption. Yet, these countries also exhibit negative effects of governance on renewable energy supply (−0.015), implying institutional bottlenecks that hinder effective implementation despite higher marginal benefits.

These results highlight the heterogeneity of transition pathways and the need for context-specific policy design, a view echoed in studies of emerging economies (Haldar & Sethi, 2023). These divergent findings imply that a single international financing model cannot serve both income groups equally.

4.3. Robustness checks

To validate these results, additional estimations using Driscoll–Kraay standard errors (Table 6) are performed to control for cross-sectional dependence and heteroskedasticity. The results remain qualitatively consistent, confirming the robustness and reliability of the findings.

Table 6. Robustness check with Driscoll-Kraay standard errors regression.

	Full sapme		Upper-middle and high-income		Low and lower-middle income	
	rsup	lemip	rsup	lemip	rsup	lemip
lgdpp	−0.3104***	1.1760***	−0.1647***	0.9474***	−0.3757***	1.1192***
	(0.0043)	(0.0216)	(0.0124)	(0.0232)	(0.0022)	(0.0138)
leni	−0.1266***	0.6149***	−0.1875***	0.8071***	−0.0997***	0.5453***
	(0.0189)	(0.0144)	(0.0193)	(0.0187)	(0.0130)	(0.0081)
lfinp	−0.0018***	−0.0031***	−0.0031***	−0.0002	−0.0002	−0.0037***
	(0.0006)	(0.0010)	(0.0004)	(0.0009)	(0.0007)	(0.0012)
gov	0.0125	−0.1481***	0.0130	−0.0968***	−0.0648***	−0.1810***
	(0.0106)	(0.0141)	(0.0155)	(0.0211)	(0.0070)	(0.0185)
rsup		−1.4982***		−0.8929***		−1.9376***
		(0.0139)		(0.0388)		(0.0675)
Constant	2.8605***	−1.4428***	1.3557***	1.0417***	3.3854***	−0.8981***
	(0.0345)	(0.1847)	(0.1640)	(0.2296)	(0.0346)	(0.1257)
Obs	1869	1869	861	861	1008	1008

Note: Standard errors are in parentheses; *, **, and *** denote statistical significance at the 5%, 1%, and 0.1% levels, respectively.

Overall, the empirical evidence indicates that while international financial assistance and governance improvements are essential for facilitating the green transition, their effectiveness depends on the structural readiness and institutional capacity of recipient countries. The results point to a policy imperative: International finance must be better aligned with domestic governance reforms to accelerate the renewable transition and achieve sustained emission reductions.

5. Conclusions and implications

In this study, we examine whether international financial assistance for clean energy can drive the energy transition and reduce emissions in developing countries. Using a Panel ARDL model with the PMG estimator on data covering 89 developing economies between 2000 and 2021, the analysis reveals a nuanced picture. While such financial inflows exert a significant long-run effect in lowering CO_2 emissions, their influence on the structural transition toward renewable energy remains limited. The persistent dominance of fossil-based energy reflects the rapid expansion of energy demand driven by industrialization and population growth; factors that outpace the deployment of renewables even amid rising financial support.

The findings also imply that governance quality plays a central role in moderating the effectiveness of international financial assistance. Economies with stronger institutions, transparent regulatory frameworks, and credible policy commitments are better positioned to translate external finance into tangible renewable capacity and sustained emission reduction. Conversely, weak governance, fragmented institutions, and inconsistent policy implementation continue to dilute the developmental and environmental impact of international assistance.

These insights highlight that the quantity of finance alone is not sufficient to accelerate the clean energy transition. Future climate finance strategies must combine financial scale with institutional strength. Mechanisms such as the GCF and JETP should embed governance-linked conditionalities, targeted technical assistance, and monitoring frameworks that ensure efficient absorption and long-term impact.

In parallel, funding should increasingly prioritize system-enabling investments, including grid modernization, energy storage, digitalization, and innovation ecosystems, that can unlock private participation and ensure the stability of renewable energy systems. Such complementary investments enhance not only technological diffusion but also local ownership and policy coherence.

In addition, innovative financing mechanisms may help overcome the structural barriers faced by developing economies during the energy transition. Hybrid financing approaches, such as blended finance structures combining concessional public capital with private investment, can reduce investment risks and mobilize larger volumes of capital for renewable energy projects. Risk-sharing instruments, guarantees, and public–private partnership frameworks may also facilitate the deployment of renewable infrastructure while lowering financing costs for developing countries.

In essence, the evidence points to a clear conclusion: Developing countries require not merely more climate finance but smarter, better-governed, and better-targeted finance. Aligning global financial mechanisms with domestic institutional capacity is thus essential for realizing a sustainable, inclusive, and irreversible clean energy transition in the developing world.

Despite providing new evidence on the role of international financial assistance in supporting the energy transition in developing countries, this study has several limitations. First, the analysis relies on the SDG 7.a.1 indicator, which captures international public financial flows supporting clean energy research, development, and production. While this measure provides a consistent cross-country dataset, it does not fully distinguish financial instruments or project types, such as grants, concessional loans, or blended finance mechanisms.

Second, governance quality is proxied using the control of corruption index, which captures an important dimension of institutional quality but does not fully reflect the broader institutional environment, including regulatory effectiveness and policy stability. In future studies, researchers could incorporate additional governance indicators to better capture institutional complexity.

Third, although the interaction-term analysis provides additional evidence on the moderating role of governance, potential endogeneity between financial flows, institutional quality, and environmental outcomes cannot be ruled out. Researchers could employ alternative identification strategies, such as instrumental variable approaches or system-GMM estimators, to strengthen causal inference.

Finally, researchers could explore the interaction between climate finance, digitalization, and circular economy strategies in supporting sustainable energy systems. These complementary factors may play an increasingly important role in enhancing the long-term effectiveness of international financial assistance.

Author contributions

Conceptualization, M.-T.B. and T.-H.L.; methodology, M.-T.B. and T.-H.L.; formal analysis, M.-T.B. and T.-H.L.; data curation, M.-T.B.; writing – original draft preparation, M.-T.B. and T.-H.L.; writing – review and editing, M.-T.B. and T.-H.L. All authors have read and agreed to the published version of the manuscript.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflict of interest.

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