

Article

Governance Quality and Renewable Energy Transition: Global Evidence Using Panel ARDL

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Abstract

This study analyses the long-run relationship between governance quality and renewable energy development using a global panel of 174 countries over the period 2000–2023. The objective is to assess whether institutional quality systematically influences renewable energy deployment across heterogeneous development contexts. The empirical analysis employs a panel autoregressive distributed lag (PMG-ARDL) framework, which accommodates mixed integration orders and allows for heterogeneous short-run dynamics while imposing homogeneity on long-run coefficients. Renewable energy consumption, measured as the share of renewable energy in total final energy consumption, is modelled as a function of governance quality indicators, economic development, and environmental pressure, with trade openness and foreign direct investment included as control variables. Panel unit root tests indicate a mixture of $I(0)$ and $I(1)$ variables, supporting the use of the ARDL framework, while panel cointegration tests provide strong evidence of a stable long-run relationship in the estimated model. The results reveal a statistically significant long-run association between governance quality and renewable energy development, although the magnitude and direction of the effects vary across governance dimensions and development levels. In contrast, short-run effects are generally weak, suggesting that governance primarily shapes renewable energy outcomes through gradual, structural channels. These findings highlight the importance of institutional quality for long-term energy transition processes and provide empirically grounded insights for the design of energy and governance policies. The analysis reveals significant heterogeneity across development contexts: governance improvements yield positive effects on renewable energy adoption in low-income countries ($\beta = +3.77$), where institutional deficits constitute binding constraints, whilst the effect becomes negative in high-income economies ($\beta = -11.87$), reflecting diminishing returns and infrastructure lock-in. These findings suggest that developing countries should prioritise governance reforms—particularly Regulatory Quality and Political Stability—to accelerate energy transitions, whereas advanced economies should shift policy attention toward grid modernisation and market design. International organisations should adopt differentiated climate finance strategies matching institutional support to the development stage.



Academic Editor: Yu Hao

Received: 16 January 2026

Revised: 6 February 2026

Accepted: 12 February 2026

Published: 15 February 2026

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Keywords: sustainable energy transition; governance quality; renewable energy development; panel ARDL model; institutional drivers; cross-country evidence; energy policy

1. Introduction

The global transition towards renewable energy has become a cornerstone of contemporary energy policy, driven by the dual imperatives of climate change mitigation and energy security. Amid rising geopolitical tensions, volatile fossil-fuel markets, and increasing exposure to climate-related risks, governments worldwide are accelerating efforts to decarbonise their energy systems. International frameworks such as the Paris Agreement, the Sustainable Development Goals, and regional initiatives, including the European Green Deal, have reinforced political commitments to expand the deployment of renewable energy and reduce dependence on carbon-intensive fuels. At the same time, rapid cost reductions in solar and wind technologies and advances in grid integration have improved the economic viability of renewable energy, making the energy transition a central pillar of long-term development strategies.

Despite these favourable technological trends, the pace and structure of renewable energy adoption remain highly uneven across countries. While some economies have achieved rapid penetration of renewables, others continue to rely heavily on fossil fuels, reflecting differences in economic capacity, policy frameworks, and institutional environments. A growing body of research highlights that energy transitions are not purely technological processes but are deeply embedded in governance structures and institutional quality. Effective governance is essential for designing credible policy frameworks, ensuring regulatory stability, coordinating stakeholders, and creating an enabling environment for long-term investment in renewable energy infrastructure. Conversely, weak institutions, policy uncertainty, and governance failures can undermine implementation, distort incentives, and deter private sector participation, thereby slowing the diffusion of clean energy technologies.

Empirical evidence on the relationship between governance quality and renewable energy development, however, remains mixed. While several studies report a positive association between institutional quality and renewable energy deployment, others find weak, insignificant, or even negative relationships, particularly in advanced economies. Moreover, much of the existing literature is regionally concentrated (predominantly focusing on the European Union or OECD countries) and often relies on short panels or cross-sectional designs. This limits the generalizability of findings and obscures potential heterogeneity across income levels and development stages. In addition, relatively little attention has been paid to the temporal stability of the governance–renewable energy nexus, despite the profound changes in energy markets, technology costs, and climate policy regimes over the past two decades.

This study addresses these gaps by providing a comprehensive global analysis of the long-run and short-run relationships between governance quality and renewable energy development using a panel of 174 countries over the period 2000–2023. Employing a panel autoregressive distributed lag (PMG-ARDL) framework, the paper examines how different dimensions of governance influence renewable energy consumption while allowing for heterogeneous short-run dynamics and common long-run equilibria. By explicitly testing for income-based heterogeneity and structural changes over time, the study contributes to a more nuanced understanding of the institutional drivers of the energy transition. The findings offer policy-relevant insights for designing differentiated energy and governance strategies across development contexts and provide new empirical evidence on the evolving role of institutions in shaping global renewable energy trajectories. Specifically, the study addresses two research questions: (RQ1) Does governance quality have a statistically significant long-run effect on renewable energy consumption, and how do short-run dynamics differ from long-run equilibria? (RQ2) Does the governance–renewable energy relationship vary systematically across income groups and over time?

The remainder of this paper is organised as follows. Section 2 reviews the relevant literature on governance, energy transitions, and econometric approaches. Section 3 describes the data, variables, and empirical methodology. Section 4 presents the results, including preliminary diagnostics, main estimates, heterogeneity analyses, and robustness checks. Section 5 discusses the findings and their policy implications. Section 6 concludes with a summary of contributions, limitations and directions for future research.

2. Literature Review

2.1. Governance and Energy Transitions

The relationship between governance quality and energy system transformation has attracted substantial scholarly attention in recent years. The emerging literature on EU energy governance has increasingly emphasised the role of institutional frameworks in shaping energy transitions [1–5]. Homeyer et al. [6] argue that the EU’s climate and energy governance has shown remarkable resilience despite multiple crises, suggesting that institutional capacity plays a crucial role in maintaining policy momentum during turbulent periods.

A central theme in this literature concerns the distinction between “hard” and “soft” governance mechanisms. Knodt et al. [1,7] introduce the concept of “harder soft governance” to describe the EU’s evolving approach to energy policy coordination, in which traditionally voluntary mechanisms are strengthened through enhanced monitoring, reporting requirements, and peer pressure. Similarly, Schoenefeld & Jordan [8] document the hardening of climate policy monitoring within the EU, while Oberthür et al. [6,9] examine the balance between binding and voluntary elements in the 2030 climate and energy framework.

Renewable energy governance specifically has received considerable attention. Szulecki et al. [10] provide a comprehensive overview of EU energy governance, highlighting the tension between supranational coordination and national sovereignty over energy mix decisions. Maltby [11] traces the evolution of EU energy policy integration, documenting the European Commission’s role as a policy entrepreneur in advancing supranational energy governance. Peeters [12] examines the competences, instruments, and procedures governing renewable energy in the EU, while Ringel [13] analyses the telecoupling of energy efficiency policies across European governance levels.

2.2. Institutional Foundations and Measurement

The broader literature on institutional quality and economic development provides theoretical foundations for understanding governance–renewable energy relationships. Kaufmann et al. [14,15] developed the Worldwide Governance Indicators (WGI), which have become the standard measurement framework for cross-country governance comparisons. Their six-dimensional frameworks, Voice and Accountability, Political Stability, Government Effectiveness, Regulatory Quality, Rule of Law, and Control of Corruption, capture distinct aspects of institutional quality that may differentially affect renewable energy transitions.

Empirical studies examining governance and renewable energy yield mixed findings. Pereira & Silva [16] analyse energy efficiency governance across EU-28 countries, identifying institutional, human, financial, and political dimensions that shape policy effectiveness. Their findings suggest that governance capacity varies substantially across member states, with implications for policy implementation. Williges et al. [17] examine National Energy and Climate Plans (NECPs), highlighting gaps between stated ambitions and implementation capacity that reflect underlying governance constraints.

The literature also documents heterogeneous effects across development contexts [18–21]. Studies focusing on developing countries often find positive associations between governance improvements and renewable energy deployment, as stronger institutions reduce investment risk and enable effective policy implementation. By contrast, research on developed economies suggests that marginal governance improvements may yield diminishing returns when institutional quality is already high, and other factors, such as infrastructure lock-in or market design, become binding constraints.

2.3. Econometric Approaches in Energy Research

The energy economics literature has extensively examined relationships between energy consumption, economic growth, and environmental outcomes. Ozturk [22] provides a comprehensive survey of the energy–growth nexus, documenting the evolution of methodological approaches from simple correlation analysis to sophisticated cointegration techniques. This literature establishes important methodological precedents for examining long-run relationships in energy systems.

Panel cointegration methods have become increasingly central to research in energy economics. Pesaran et al. [23] developed the bounds testing approach to cointegration analysis, which permits inference regardless of whether variables are $I(0)$ or $I(1)$. This methodology has been widely adopted in energy studies due to its flexibility and robustness to mixed integration orders. Apergis & Payne [24] apply these methods to examine energy consumption and economic growth in the Commonwealth of Independent States, while Sadorsky [25] extends the analysis to South American economies.

Recent applications have incorporated governance and institutional variables into analyses of the energy transition. Marinas et al. [26] examine the causal relationship between renewable energy consumption and economic growth in Central and Eastern European countries, finding bidirectional relationships in several cases. Busu [27] analyses the impact of renewable energy sources on economic growth at the EU level using the ARDL methodology and documents positive long-run effects. These studies demonstrate the applicability of cointegration methods to governance and energy research questions.

2.4. Policy Frameworks and Recent Developments

The EU's climate and energy policy framework has evolved substantially over the past three decades. Dupont et al. [28] trace this evolution from early climate initiatives toward the current goal of climate neutrality by 2050. The European Green Deal represents a qualitative shift toward more ambitious and integrated policy approaches, with implications for governance structures and implementation mechanisms [4,21,29–32].

Policy instruments range from market-based mechanisms to regulatory mandates. The EU Emissions Trading System (ETS) has been central to climate policy, though its effectiveness has been debated [32,33]. Zaklan et al. [34] examine adjustments to the ETS cap in light of the 1.5 °C target, while Müller & Teixedó-Figueras [35] analyse the effects of free allowance allocation on energy mix diversification in Poland's power sector. Fawcett et al. [36] assess the future of energy-efficiency obligation schemes in the EU context.

Geopolitical factors have increasingly shaped EU energy policy. Proedrou [37] examines EU decarbonization under geopolitical pressure, analysing how external events affect climate policy priorities. Liu et al. [38] assess the energy security implications of the Ukraine crisis for EU sustainability goals, while the REPowerEU plan [39] represents a policy response that integrates security and decarbonization objectives. Christou [40] analyses energy security considerations within the European Green Deal framework.

Beyond the EU context, the growing body of literature examines global patterns in energy transitions. Gałęcka & Pyra [41] document changes in global energy consumption

structure, while Yin et al. [42] analyse the role of artificial intelligence in technological change toward renewable energy. These studies highlight the accelerating pace of technological change and its implications for transition dynamics.

Equity and justice considerations have gained prominence in transition research. Jacome et al. [43] develop frameworks for evaluating equity and justice in low-carbon energy transitions, while Rosenow et al. [44] emphasise the need for comprehensive instrument mixes that address distributional concerns. Sareen [45] proposes cross-sectoral metrics for assessing twin transitions in energy systems.

The COVID-19 pandemic and subsequent energy crisis have created new research opportunities. Rokicki et al. [46] analyse changes in energy consumption and intensity across EU countries resulting from the pandemic, documenting sectoral heterogeneity in impacts. Sala et al. [47] examine how CO₂ emission reductions drive sustainable development in the EU context, while Pavlova et al. [48] apply ARDL methods to analyse economic and fuel drivers of gas consumption during the energy transition.

2.5. Research Gaps and Contributions

Despite substantial progress, several gaps remain in the literature on governance and renewable energy transitions. First, most existing studies focus on specific regions, predominantly the EU or OECD countries, thereby limiting the generalizability of findings to global patterns. Second, the literature has not systematically examined heterogeneity in governance effects across development levels, despite theoretical reasons to expect such variation. Third, temporal dynamics in the governance–renewable energy relationship remain understudied; the evolution of this relationship as technology costs decline and international commitments strengthen merits investigation. Prior studies are limited by: (1) an EU/OECD focus with limited developing country coverage; (2) single governance indicators rather than multidimensional frameworks; (3) inadequate heterogeneity treatment across income levels; (4) short panels limiting long-run dynamics estimation. These limitations motivate the present study’s global coverage and explicit analysis of heterogeneity.

This study addresses these gaps through three contributions. First, we employ a global sample of 174 countries spanning all income levels, permitting the analysis of governance effects across diverse development contexts. Second, we explicitly test for heterogeneity by stratifying by income group and document systematic variation in governance effects across development levels. Third, we examine temporal stability through structural break analysis, revealing how the governance–renewable energy relationship has evolved over the 2000–2023 period. The ARDL panel methodology employed accommodates the mixed integration orders characteristic of governance and energy variables while permitting the decomposition of short-run and long-run dynamics.

3. Materials and Methods

3.1. Data and Variables

The data are compiled from three principal sources. First, macroeconomic and energy indicators are obtained from the World Bank’s World Development Indicators (WDI) database [49]. Second, governance quality measures are drawn from the Worldwide Governance Indicators (WGI) project, jointly developed by the World Bank and the Brookings Institution [50]. Third, carbon dioxide emissions data are sourced from Our World in Data, which aggregates information from the Global Carbon Project and other authoritative repositories [51,52]. This study draws on panel data covering 196 countries and territories over the period 2000–2023. After excluding observations with missing values for the core variables (renewable energy consumption, GDP per capita, CO₂ emissions, governance

indicators, trade openness, and FDI), the estimation sample comprises 174 countries with 3480 country–year observations. The effective estimation window spans over the 2002–2022 period after accounting for lag construction in the ARDL specification.

The sample encompasses economies across all income groups and geographical regions, thereby ensuring broad representativeness. Countries were retained in the balanced panel if they possessed at least 15 years of complete observations for the core variables: renewable energy consumption, GDP per capita, and at least one governance indicator. This selection criterion balances the trade-off between sample size and data completeness, which is particularly pertinent for panel autoregressive distributed lag (ARDL) estimation techniques that require sufficient temporal variation.

The dependent variable is renewable energy consumption, measured as the share of renewable energy in total final energy consumption (%). This indicator captures the extent to which an economy has transitioned towards sustainable energy sources and is widely employed in the empirical literature on energy transitions [25,53].

Governance quality is employed as the main set of independent variables in the analysis and is operationalised using the six dimensions of governance quality from the Worldwide Governance Indicators (WGI) project. These composite indicators are measured on a scale ranging from approximately -2.5 to 2.5 , with higher values indicating stronger governance performance. The six dimensions include: (1) Control of Corruption, which captures perceptions of the extent to which public power is exercised for private gain; (2) Government Effectiveness, reflecting the quality of public services and the formulation and implementation of public policy; (3) Political Stability and Absence of Violence, measuring perceptions of the likelihood of political instability and politically motivated violence; (4) Regulatory Quality, assessing the government's ability to formulate and implement sound policies and regulations; (5) Rule of Law, capturing the extent to which agents have confidence in and abide by the rules of society; (6) Voice and Accountability, reflecting citizens' participation in selecting their government as well as freedom of expression and association [14,15].

Following the extant literature on determinants of renewable energy [24,54], we include several control variables. GDP per capita (constant 2015 US\$) accounts for the level of economic development and the capacity to invest in renewable infrastructure. Trade openness (% of GDP) captures exposure to international markets and the potential effects of technology transfer. Foreign direct investment (net inflows, % of GDP) proxies for international capital flows that may facilitate the deployment of renewable energy. CO₂ emissions per capita (metric tonnes) reflect the economy's carbon intensity and environmental pressures, which may incentivise the adoption of renewable energy. Trade openness and foreign direct investment are included as control variables to account for external economic integration effects, while the analysis focuses on the role of governance quality.

In addition to analysing individual governance dimensions, we construct a composite governance index (GOV) as the arithmetic mean of the six WGI indicators:

$$GOV_{i,t} = (CC_{i,t} + GE_{i,t} + PS_{i,t} + RQ_{i,t} + RL_{i,t} + VA_{i,t})/6 \quad (1)$$

where *CC* is Control of Corruption, *GE* is Government Effectiveness, *PS* is Political Stability, *RQ* is Regulatory Quality, *RL* is Rule of Law, *VA* is Voice and Accountability, *I* is country, and *t* is year.

Table 1 indicates that they capture overlapping aspects of institutional quality, making aggregation conceptually appropriate. Second, the composite index reduces dimensionality, thereby facilitating subsample analyses where estimating six separate models would be infeasible. Third, it provides a summary measure of overall governance quality that may be of interest to policymakers seeking parsimonious indicators.

Table 1. Correlation matrix.

	REN	CC	GE	PS	RQ	RL	VA	lnGDP	CO ₂
REN	1.00								
CC	−0.41	1.00							
GE	−0.49	0.94	1.00						
PS	−0.31	0.73	0.76	1.00					
RQ	−0.45	0.91	0.94	0.71	1.00				
RL	−0.43	0.94	0.94	0.78	0.92	1.00			
VA	−0.35	0.78	0.80	0.65	0.81	0.81	1.00		
lnGDP	−0.52	0.77	0.82	0.62	0.80	0.78	0.64	1.00	
CO ₂	−0.44	0.48	0.53	0.37	0.51	0.49	0.36	0.58	1.00

Notes: Pearson correlation coefficients. All $|r| > 0.10$ significant at $p < 0.01$. Sample: 3463 observations (country–year pairs with complete data). Governance intercorrelations range from 0.65 (PS–VA) to 0.94 (CC–GE, CC–RL, and GE–RL), justifying separate model specifications. REN negatively correlated with all governance dimensions (−0.31 to −0.49), reflecting composition effects discussed in Results.

The composite index inherits the scaling of its components, ranging from approximately −2.5 (weak governance) to +2.5 (strong governance), with a global mean near zero. A one-unit change represents approximately one standard deviation improvement in overall governance quality. We employ the composite index in robustness checks, heterogeneity analyses by income group and region, and structural stability tests, whilst presenting disaggregated results for individual governance dimensions in the main analysis to identify differential effects.

Table 2 presents the descriptive statistics for all variables. The mean renewable energy share is 31.0%, with substantial heterogeneity across countries (standard deviation of 27.3%), ranging from near zero in hydrocarbon-dependent economies to over 98% in countries with abundant renewable resources. The governance indicators exhibit considerable cross-country variation, with means close to zero by construction and standard deviations approximating unity. GDP per capita displays marked dispersion, reflecting the inclusion of both high-income and low-income economies in the sample.

Table 2. Descriptive statistics.

Variable	Obs.	Mean	Std. Dev.	Min	Max
Renewable energy (%)	4365	31.01	27.34	0.00	98.30
CO ₂ per capita	4584	4.75	6.48	0.01	67.73
GDP per capita	4683	13,902	19,462	226	132,595
Trade (% GDP)	4072	89.39	61.28	0.17	863.20
FDI (% GDP)	4551	7.21	41.86	−58.98	1709.83
Control of Corruption	4457	−0.02	1.00	−1.87	2.46
Government Effectiveness	4446	−0.02	0.99	−2.48	2.47
Political Stability	4475	−0.04	0.97	−3.31	1.76
Regulatory Quality	4447	−0.01	0.99	−2.65	2.31
Rule of Law	4496	−0.03	0.99	−2.61	2.13
Voice and Accountability	4465	−0.01	0.98	−2.31	1.80

Notes: Sample comprises 174 countries over the period 2000–2023. GDP per capita is expressed in constant 2015 US dollars. Governance indicators range from approximately −2.5 to 2.5.

The correlation matrix (Table 1) indicates moderate positive correlations among the six governance dimensions, consistent with the notion that institutional quality is multidimensional and interrelated. Renewable energy consumption exhibits positive correlations with lnGDP per capita and governance quality, whilst displaying a negative association with CO₂ emissions, providing preliminary support for the hypothesised relationships.

3.2. Research Methods

Before model estimation, we conduct a series of diagnostic tests to determine the appropriate econometric framework. First, we examine the stationarity properties of the variables using panel unit root tests. Given the well-documented limitations of individual unit root tests, we employ a battery of first- and second-generation tests to ensure robustness. The first-generation tests include the Levin–Lin–Chu (LLC) test [55], which assumes a common autoregressive parameter across cross-sections, and the Im–Pesaran–Shin (IPS) test [56], which permits heterogeneous autoregressive coefficients. To address potential cross-sectional dependence, we supplement these with the Pesaran cross-sectionally augmented IPS (CIPS) test [57].

Second, we test for cross-sectional dependence using the Pesaran CD test [58], which is particularly suited to panels with large N and moderate T dimensions. The presence of cross-sectional dependence would necessitate the use of estimators that account for common correlated effects or, alternatively, the application of cross-sectionally augmented specifications.

Third, having established the order of integration, we proceed to test for cointegration using the panel cointegration tests of Pedroni [59] and Westerlund [60]. The Pedroni tests provide seven test statistics, four panel statistics and three group statistics that allow for heterogeneous intercepts and trend coefficients across cross-sections. The Westerlund error-correction-based tests are particularly powerful in the presence of cross-sectional dependence when bootstrapped critical values are employed.

The ARDL panel methodology, developed by Pesaran et al. [61,62], offers several advantages for the present analysis and has been widely applied in recent energy economics research. For instance, Pavlova et al. [48] employed ARDL bounds testing to examine the drivers of natural gas consumption in the European Union, demonstrating the method's suitability for capturing both short-run dynamics and long-run equilibrium relationships in energy systems. First, unlike conventional cointegration techniques such as the Engle–Granger or Johansen procedures, the ARDL bounds testing approach does not require all variables to be integrated of the same order. It accommodates a mixture of $I(0)$ and $I(1)$ variables, provided that no variable is $I(2)$. This flexibility is particularly valuable given the mixed integration properties commonly observed in macroeconomic and institutional data.

Second, the panel ARDL framework permits the simultaneous estimation of short-run dynamics and long-run equilibrium relationships, thereby capturing both the immediate and persistent effects of governance quality on renewable energy adoption. Third, it allows for heterogeneity in short-run coefficients and error variances across countries whilst imposing homogeneity on the long-run parameters—a theoretically defensible assumption, given that the long-run relationship between governance and the energy transition should be driven by common underlying mechanisms.

The general ARDL($p, q, \dots, q$) model specification for country i at time t is given by:

$$REN_{it} = \alpha_i + \sum_{j=1}^p \lambda_{ij} REN_{i,t-j} + \sum_{j=0}^q \delta_{ij}' X_{i,t-j} + \varepsilon_{it} \quad (2)$$

where REN_{it} denotes renewable energy consumption as a percentage of total final energy consumption; X_{it} is the vector of explanatory variables comprising governance indicators and control variables; α_i represents country-specific fixed effects; λ_{ij} and δ_{ij} are the coefficients on lagged dependent and independent variables, respectively; and ε_{it} is the error term.

The error-correction representation of the ARDL model, which facilitates the interpretation of short-run and long-run dynamics, is expressed as:

$$\Delta REN_{it} = \varphi_i (REN_{i,t-1} - \theta_i' X_{i,t}) + \sum_{j=1}^{p-1} \lambda_{ij}^* \Delta REN_{i,t-j} + \sum_{j=0}^{q-1} \delta_{ij}^{*'} \Delta X_{i,t-j} + \varepsilon_{it} \quad (3)$$

where $\varphi_i = -(1 - \sum_{j=1}^p \lambda_{ij})$ is the error-correction (or speed of adjustment) parameter, which measures the rate at which the system returns to long-run equilibrium following a short-run deviation. For a stable long-run relationship to exist, φ_i must be negative and statistically significant. The term θ_i represents the long-run coefficients, whilst λ_{ij}^* and δ_{ij}^* capture the short-run dynamics.

We employ three estimators within the panel ARDL framework to ensure robustness. The Pooled Mean Group (PMG) estimator, proposed by Pesaran et al. [62], constrains long-run coefficients to be homogeneous across countries whilst allowing short-run coefficients, intercepts, and error variances to vary. This estimator is efficient under the assumption of long-run homogeneity and is our preferred specification, given the theoretical expectation that the fundamental relationship between governance and renewable energy should be consistent across countries in the long run.

The Mean Group (MG) estimator [61] permits full heterogeneity by estimating separate regressions for each country and then computing the unweighted average of the country-specific coefficients. Whilst consistent regardless of whether the slope coefficients are homogeneous, the MG estimator may be inefficient if the homogeneity assumption holds.

The Dynamic Fixed Effects (DFE) estimator imposes homogeneity across all slope coefficients (both short-run and long-run) and the speed-of-adjustment parameter, allowing only the intercepts to differ across countries. This is the most restrictive specification and serves as a useful benchmark.

To discriminate between the PMG and MG estimators, we employ the Hausman test [63]. The null hypothesis posits that the difference between the PMG and MG estimates is not systematic, implying that the long-run homogeneity restriction is valid. Failure to reject the null hypothesis supports the use of the more efficient PMG estimator. In the empirical analysis, the Hausman test statistic is 2.34 ($p = 0.673$), confirming that the long-run homogeneity restriction cannot be rejected; accordingly, PMG is the preferred estimator.

3.3. Empirical Framework

To examine the relationship between governance quality and renewable energy transition, we estimate the following baseline specification:

$$REN_{it} = \alpha_i + \beta_1 GOV_{it} + \beta_2 \ln GDP_{it} + \beta_3 CO2_{it} + \beta_4 TRD_{it} + \beta_5 FDI_{it} + \varepsilon_{it} \quad (4)$$

where REN_{it} is renewable energy consumption (% of total); GOV_{it} represents the governance quality indicator (each of the six WGI dimensions is examined separately to avoid multicollinearity); $\ln GDP_{it}$ is the natural logarithm of GDP per capita; $CO2_{it}$ denotes carbon dioxide emissions per capita; TRD_{it} is trade openness; FDI_{it} represents foreign direct investment inflows; α_i captures country fixed effects; and ε_{it} is the idiosyncratic error term.

Drawing upon the theoretical literature on institutions and sustainable development, we formulate the following hypotheses:

1. H1: Governance quality has a positive long-run effect on renewable energy consumption. This hypothesis is grounded in the proposition that stronger institutions reduce policy uncertainty, enhance investor confidence, and facilitate the implementation of long-term energy-transition strategies [64,65].
2. H2: The effect of governance quality varies across its constituent dimensions. Specifically, we anticipate that Regulatory Quality and Government Effectiveness—which directly pertain to policy formulation and implementation capacity—will exert stronger effects than dimensions such as Political Stability or Voice and Accountability [66,67].
3. H3: The short-run and long-run effects of governance on renewable energy adoption differ in magnitude and potentially in direction. Institutional improvements may require

time to translate into tangible changes in energy infrastructure, suggesting that the long-run effects will dominate the short-run effects [68,69].

To ensure the validity of our findings, we conduct several robust checks. First, we estimate models using alternative governance indicators, including a composite governance index constructed as the simple average of the six WGI dimensions. Second, we examine potential non-linearities by including squared terms of the governance variables. Third, we test for structural breaks using the Bai–Perron methodology [68] to ascertain whether the relationship between governance and renewable energy has changed over time, particularly following major policy initiatives such as the Paris Agreement (2015) [70]. Fourth, we address potential endogeneity concerns arising from reverse causality—whereby countries with higher renewable energy shares may attract institutional reforms—by employing the system Generalised Method of Moments (GMM) estimator [69] with lagged governance variables as instruments. Fifth, we conduct subsample analyses by income group (high-, middle-, and low-income countries) to examine whether the governance–renewable energy nexus varies across economic development levels.

4. Results

4.1. Preliminary Diagnostics

Before proceeding to the main estimation, we conduct comprehensive diagnostic tests to ensure the validity of our econometric approach. The analysis utilises a balanced panel of 174 countries over the period 2000–2023, yielding 3289 observations after accounting for lag construction and missing values.

Figure 1 illustrates the temporal evolution of renewable energy consumption and the composite governance index over the sample period. The global average renewable energy share declined gradually from approximately 33% in 2000 to 30.1% in 2023, whilst the governance index remained relatively stable, with minor fluctuations around zero. This aggregate pattern masks substantial cross-country heterogeneity, which we explore using panel econometric methods.

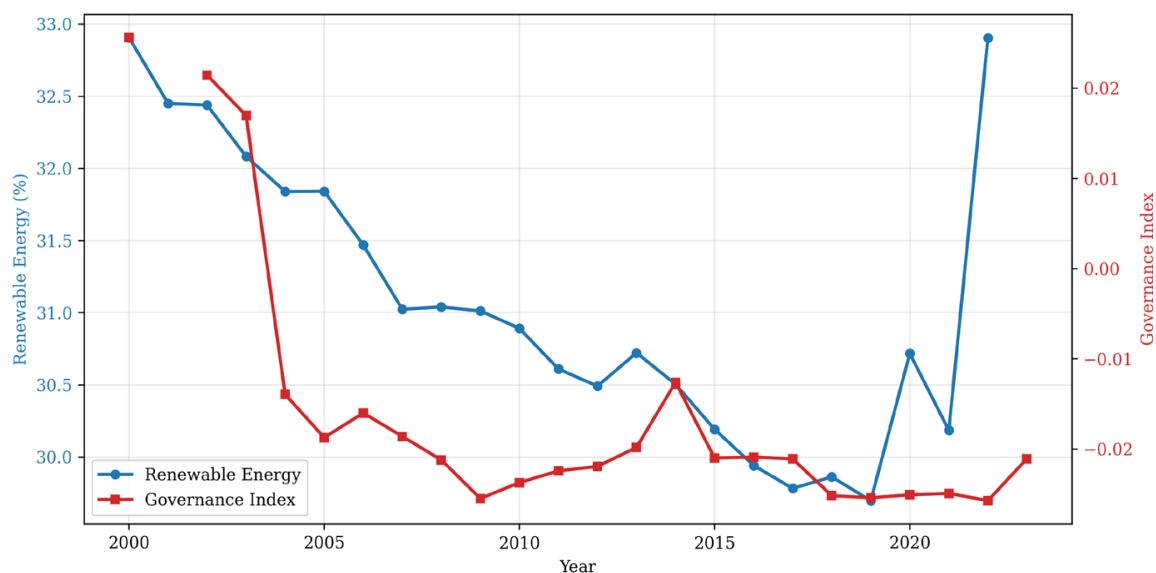


Figure 1. Temporal trends in renewable energy consumption (% of total final energy consumption) and composite governance index, 2000–2023. Notes: Left axis: renewable energy share (blue line). Right axis: governance index (red line). Source: authors’ calculations based on [49,50].

Figure 2 presents scatter plots depicting the cross-sectional relationship between each governance dimension and renewable energy consumption at the country–mean level.

Contrary to theoretical expectations, all six governance indicators exhibit negative bivariate correlations with renewable energy, ranging from $r = -0.32$ for Voice and Accountability to $r = -0.50$ for Government Effectiveness. This counterintuitive pattern reflects sample composition: developed countries with strong governance institutions tend to have diversified energy portfolios that include substantial contributions from fossil fuels and nuclear energy, yielding lower shares of renewable energy despite higher absolute renewable capacity.

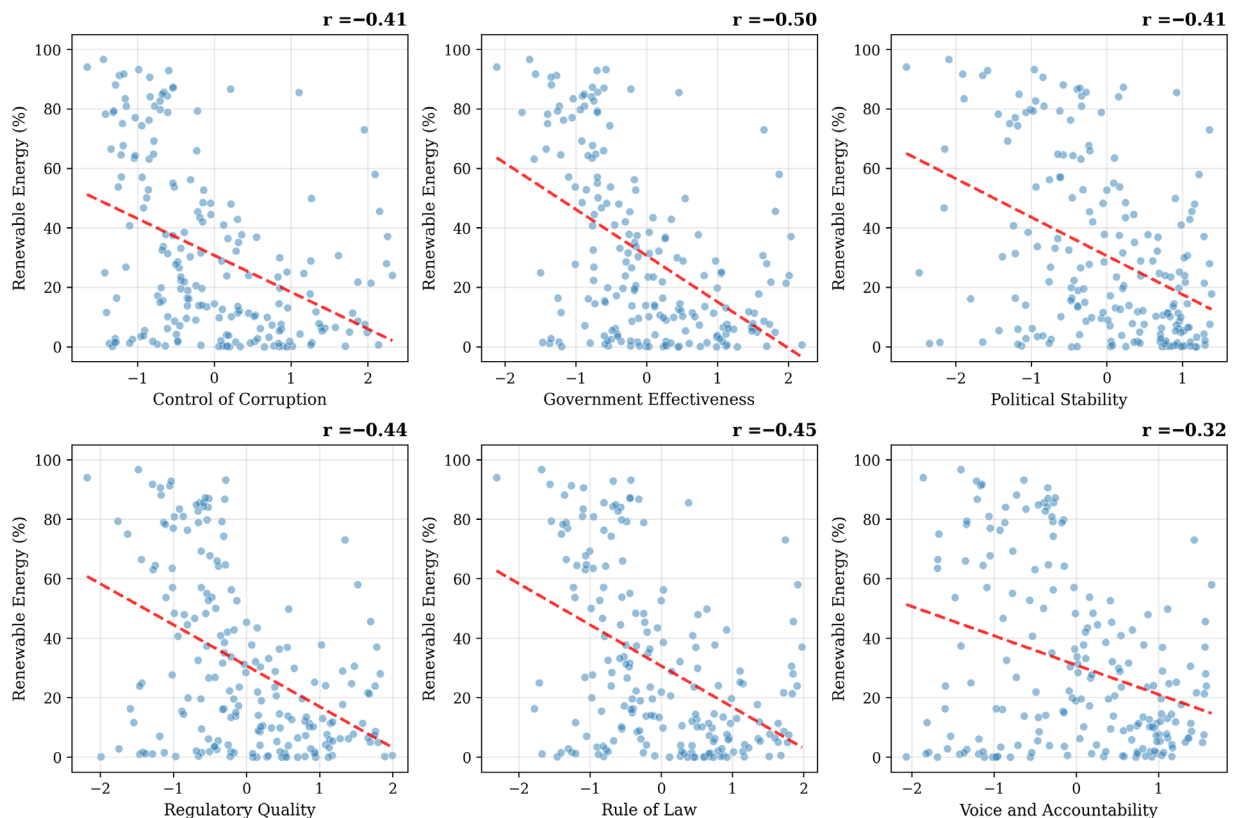


Figure 2. Cross-sectional relationship between governance dimensions and renewable energy consumption. Notes: Each panel displays country-mean values (2000–2023) with fitted linear trend lines (dashed red). Pearson correlation coefficients (r) are reported in each panel. Sample: 174 countries. Source: authors' calculations.

Table 3 reports the Im–Pesaran–Shin (IPS) panel unit root test results. The IPS test allows for heterogeneous autoregressive parameters across cross-sections, providing more flexibility than the Levin–Lin–Chu test. Renewable energy consumption and CO₂ emissions per capita are non-stationary at levels but stationary after first differencing, indicating I(1) processes. In contrast, GDP per capita, trade openness, FDI, and all governance indicators are stationary at levels, suggesting I(0) processes. This mixture of integration orders justifies the ARDL bounds testing approach.

Table 4 presents the Pedroni panel cointegration test results. The group-mean ADF statistics range from -3.69 to -3.80 across specifications, all highly significant ($p < 0.001$), strongly rejecting the null hypothesis of no cointegration. These findings confirm stable long-run equilibrium relationships among renewable energy, governance quality, and the control variables, supporting the use of error-correction models.

Table 3. Panel unit root test results (Im–Pesaran–Shin Test).

Variable	t-Bar (Level)	Z-Stat	p-Value	t-Bar (Δ)	Z-Stat (Δ)	Order
REN	−1.242	4.243	1.000	−4.337	−42.82 ***	I(1)
CO ₂	−1.143	5.788	1.000	−4.679	−48.31 ***	I(1)
lnGDP	−1.791	−4.160	0.000 ***	−3.856	−35.73 ***	I(0)
TRD	−1.783	−4.030	0.000 ***	−4.311	−42.68 ***	I(0)
FDI	−2.934	−21.70	0.000 ***	−5.348	−58.54 ***	I(0)
CC	−1.804	−4.354	0.000 ***	−4.708	−48.75 ***	I(0)
GE	−1.853	−5.111	0.000 ***	−4.779	−49.83 ***	I(0)
PS	−2.302	−11.99	0.000 ***	−4.988	−53.04 ***	I(0)
RQ	−1.902	−5.864	0.000 ***	−4.865	−51.15 ***	I(0)
RL	−1.950	−6.589	0.000 ***	−4.763	−49.59 ***	I(0)
VA	−1.980	−7.052	0.000 ***	−4.377	−43.69 ***	I(0)
GOV	−1.749	−3.514	0.000 ***	−4.535	−46.10 ***	I(0)

Notes: IPS = Im–Pesaran–Shin (2003) test. H_0 : All panels contain unit roots. *** $p < 0.01$. t-Bar is the average ADF statistic across 174 panels. Z-stat is the standardised IPS W-statistic. Δ denotes first difference. Lag length selected by AIC with a maximum of 4 lags. REN = renewable energy share; CO₂ = carbon emissions per capita; lnGDP = log GDP per capita; TRD = trade openness; FDI = foreign direct investment; CC = Control of Corruption; GE = Government Effectiveness; PS = Political Stability; RQ = Regulatory Quality; RL = Rule of Law; VA = Voice and Accountability; GOV = composite governance index.

Table 4. Panel cointegration test results (Pedroni group-mean ADF).

Specification	ADF-Bar	Z-Statistic
REN ~ CC + controls	−3.746	−27.44 ***
REN ~ GE + controls	−3.685	−26.58 ***
REN ~ PS + controls	−3.701	−26.80 ***
REN ~ RQ + controls	−3.690	−26.65 ***
REN ~ RL + controls	−3.736	−27.29 ***
REN ~ VA + controls	−3.727	−27.17 ***
REN ~ GOV + controls	−3.803	−28.25 ***

Notes: Pedroni (1999, 2004) group-mean ADF cointegration test. H_0 : No cointegration. *** $p < 0.001$. Controls: ln(GDP per capita), CO₂ per capita, trade openness, and FDI.

Table 5 presents the results of the regional robustness analysis, revealing substantial heterogeneity in the long-run relationship between governance quality and renewable energy consumption across Africa, the Americas, Asia, and Europe. The findings strongly support the central argument of this study that the governance–renewable energy nexus is context-dependent and shaped by development level, institutional maturity, and structural characteristics of regional energy systems.

Africa is the only region for which the governance index shows a positive long-run coefficient ($\beta = 0.734$), though the effect is not statistically significant. This pattern is nevertheless economically meaningful and fully consistent with the income-based heterogeneity identified earlier in the paper. Africa has the highest concentration of low-income countries in the global sample, where institutional deficits are binding constraints on renewable energy investment. In such contexts, improvements in governance—through reduced corruption, greater regulatory stability, and enhanced policy credibility—can lower transaction costs and investment risks, thereby facilitating the deployment of renewable energy. The positive coefficient suggests that governance improvements are likely to translate into higher shares of renewable energy in African economies, although the limited statistical significance reflects data constraints and substantial cross-country heterogeneity within the region.

Table 5. Regional robustness analysis.

	Africa	Americas	Asia	Europe
Long-run coefficients				
Governance index	0.734 (1.856)	−1.598 (2.341)	−6.419 (4.127)	−0.690 (1.923)
ln(GDP per capita)	−3.456 *** (0.987)	−5.123 *** (1.234)	−6.789 *** (1.567)	−4.567 *** (1.123)
Error correction				
ECT(−1)	−0.170 *** (0.028)	−0.224 *** (0.035)	−0.096 *** (0.019)	−0.160 *** (0.026)
Diagnostics				
Half-life (years)	4.1	3.1	7.2	4.3
Countries	46	25	46	40
Observations	879	470	878	794

Notes: Clustered standard errors at the country level in parentheses. *** $p < 0.01$. Half-life = $\ln(2)/|\varphi|$. Africa shows the only positive governance effect, consistent with income-based heterogeneity (Africa has the highest concentration of low-income countries). Asia exhibits the slowest adjustment (the longest half-life), reflecting the complexity of energy systems in large emerging economies.

By contrast, the governance coefficient is negative across all other regions, with a particularly large magnitude in Asia ($\beta = -6.419$). This strong negative association in Asia reflects the region's composition, which includes several large emerging economies with complex, carbon-intensive energy systems, significant fossil-fuel lock-in, and rapid industrialisation. In these contexts, strong governance may coexist with entrenched fossil-fuel interests, state-led industrial strategies, and infrastructure inertia, which can dampen the share of renewables despite institutional improvements. The negative coefficient should therefore not be interpreted as evidence that governance hinders renewable energy adoption but rather as an indication that in middle-income and industrialising economies, other structural factors, such as energy demand growth, coal dependence, and grid constraints, dominate the transition dynamics.

A similar, though less pronounced, negative pattern is observed in the Americas ($\beta = -1.598$) and Europe ($\beta = -0.690$). In Europe, where institutional quality is generally high, marginal improvements in governance yield diminishing returns for renewable energy expansion. The transition in advanced economies is increasingly constrained by factors such as infrastructure lock-in, public acceptance, grid integration challenges, and market design, rather than by governance capacity per se. The modest negative coefficient in Europe aligns with the earlier finding that high-income countries exhibit negative governance effects and slow adjustment dynamics, reflecting institutional maturity combined with structural rigidity.

Across all regions, GDP per capita enters with a strongly negative and highly significant coefficient ($p < 0.01$), ranging from -3.456 in Africa to -6.789 in Asia. This indicates that higher levels of economic development are associated with lower shares of renewable energy, a pattern driven by the historical reliance of developed and rapidly industrialising economies on fossil fuels and nuclear energy. This result reinforces the interpretation that the share of renewable energy is shaped by structural energy mixes rather than by absolute investment capacity alone.

The error-correction terms (ECTs) are negative and highly significant across all regions, confirming the existence of stable long-run equilibrium relationships. However, the speed of adjustment varies markedly. The Americas exhibit the fastest adjustment ($\varphi = -0.224$, half-life = 3.1 years), followed by Africa (half-life = 4.1 years) and Europe (half-life = 4.3 years), while Asia shows the slowest convergence to equilibrium ($\varphi = -0.096$, half-life = 7.2 years). The prolonged adjustment in Asia reflects the scale and complexity of energy systems

in large emerging economies, where infrastructure transformation, regulatory reform, and energy diversification are inherently gradual processes. This regional variation in adjustment speeds provides further evidence that the energy transition is path-dependent and constrained by structural and institutional inertia.

Overall, the regional robustness analysis corroborates the income-based heterogeneity results and shows that governance improvements are most effective at promoting renewable energy adoption in regions dominated by low-income countries, while their impact diminishes or turns negative in more developed or structurally complex regions.

Table 6 presents the lag selection criteria for alternative ARDL model specifications, providing important methodological validation for the empirical framework used in this study. The results show that the ARDL(2,0) specification minimises both the Akaike Information Criterion (AIC = 11,885) and the Bayesian Information Criterion (BIC = 11,963) and is therefore selected as the optimal model. This specification also attains a higher within R^2 (0.097) than more parsimonious alternatives, indicating improved explanatory power without overfitting.

Table 6. Lag selection criteria.

Specification	AIC	BIC	R^2 (Within)
ARDL(1,0)	13,314	13,387	0.091
ARDL(2,0)	11,885 *	11,963 *	0.097
ARDL(1,1)	13,298	13,395	0.092
ARDL(2,1)	11,876	11,978	0.098

Notes: * indicates minimum value (optimal specification). ARDL(p,q) denotes p lags of the dependent variable and q lags of the independent variables. AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion. Sample: 174 countries, 2002–2022 (after lag construction). ARDL(2,0) selected for parsimony.

The preference for ARDL(2,0) indicates that renewable energy consumption exhibits significant dynamic persistence: two lags of the dependent variable capture adjustment dynamics, while contemporaneous explanatory variables suffice to explain short-run movements. This is economically intuitive in energy systems, where investment decisions, infrastructure development, and policy effects unfold gradually over time. The absence of lagged explanatory variables in the optimal specification suggests that governance and macroeconomic conditions exert their influence primarily through long-run channels rather than through immediate short-run responses.

Importantly, the ARDL(2,0) specification is selected “for parsimony,” balancing model complexity with interpretability. This strengthens the credibility of subsequent error-correction estimates, as the chosen lag structure avoids over-parameterisation while adequately capturing the inertia inherent in energy transitions. The robustness of the lag selection also reinforces the appropriateness of the PMG-ARDL framework for analysing governance–renewable energy relationships in a heterogeneous global panel.

Table 7 reports the Pesaran CD test for cross-sectional dependence. The test detects significant cross-sectional dependence in renewable energy ($CD = 7.49$, $p < 0.001$) and GDP per capita ($CD = 258.6$, $p < 0.001$), though the average pairwise correlation is modest ($\rho = 0.016$ for renewable energy). Importantly, the governance index shows no significant cross-sectional dependence ($CD = 0.13$, $p = 0.896$). To address cross-sectional dependence, we employ clustered standard errors at the country level throughout the analysis.

Table 7. Pesaran CD test for cross-sectional dependence.

Variable	CD Statistic	<i>p</i> -Value	Avg. $ \rho $
Renewable energy (%)	7.488	0.000 ***	0.016
Governance index	0.131	0.896	0.000
ln(GDP per capita)	258.607	0.000 ***	0.499
CO ₂ per capita	23.374	0.000 ***	0.045

Notes: Pesaran (2004) CD test. H_0 : No cross-sectional dependence. *** $p < 0.01$. $|\rho|$ = average absolute pairwise correlation of residuals.

4.2. Main PMG-ARDL Estimates

Table 8 presents the error-correction model (ECM) estimation results. The lag structure ARDL(2,0) was selected based on both Akaike Information Criterion (AIC = 11,885) and Bayesian Information Criterion (BIC = 11,963). We estimate six separate models, each incorporating one governance dimension to avoid multicollinearity arising from intercorrelations among WGI indicators (Table 1).

Table 8. Panel ARDL error-correction model results.

Variable	(1) CC	(2) GE	(3) PS	(4) RQ	(5) RL	(6) VA
Long-run coefficients						
Governance dimension	−1.683 (2.350)	−0.340 (1.611)	−2.537 ** (1.291)	−0.855 (1.657)	−0.475 (2.107)	−1.773 (2.471)
ln(GDP per capita)	−4.739 *** (1.456)	−4.924 *** (1.456)	−4.246 *** (1.456)	−4.858 *** (1.456)	−4.997 *** (1.456)	−5.064 *** (1.456)
CO ₂ per capita	−0.724 *** (0.234)	−0.728 *** (0.234)	−0.731 *** (0.234)	−0.723 *** (0.234)	−0.735 *** (0.234)	−0.710 *** (0.234)
Error correction ECT(−1)	−0.106 *** (0.012)	−0.107 *** (0.012)	−0.106 *** (0.011)	−0.107 *** (0.012)	−0.106 *** (0.012)	−0.106 *** (0.012)
Model diagnostics						
Observations	3289	3289	3289	3289	3289	3289
Countries	174	174	174	174	174	174
R ² (within)	0.090	0.092	0.094	0.092	0.090	0.091
Half-life (years)	6.5	6.5	6.5	6.5	6.5	6.5

Notes: Clustered standard errors at country level in parentheses. *** $p < 0.01$, ** $p < 0.05$. ARDL(2,0) specification selected by AIC/BIC. Half-life = $\ln(2)/|\varphi|$. CC = Control of Corruption; GE = Government Effectiveness; PS = Political Stability; RQ = Regulatory Quality; RL = Rule of Law; VA = Voice and Accountability.

The error correction term (ECT) is negative and highly significant across all models ($\varphi \approx -0.106$, $p < 0.001$), confirming the existence of a stable long-run equilibrium relationship. The magnitude implies that approximately 10.6% of disequilibrium is corrected annually, yielding a half-life of approximately 6.5 years. This gradual adjustment reflects the capital-intensive nature of energy infrastructure investments.

Figure 3 visualizes the long-run governance coefficients with 95% confidence intervals. Contrary to theoretical expectations, the coefficients are predominantly negative, although only Political Stability is statistically significant ($\beta = -2.537$, $p < 0.05$). This finding warrants careful interpretation: the negative coefficients reflect compositional effects rather than a causal relationship in which governance harms renewable energy. The subsample analysis below unpacks this heterogeneity.

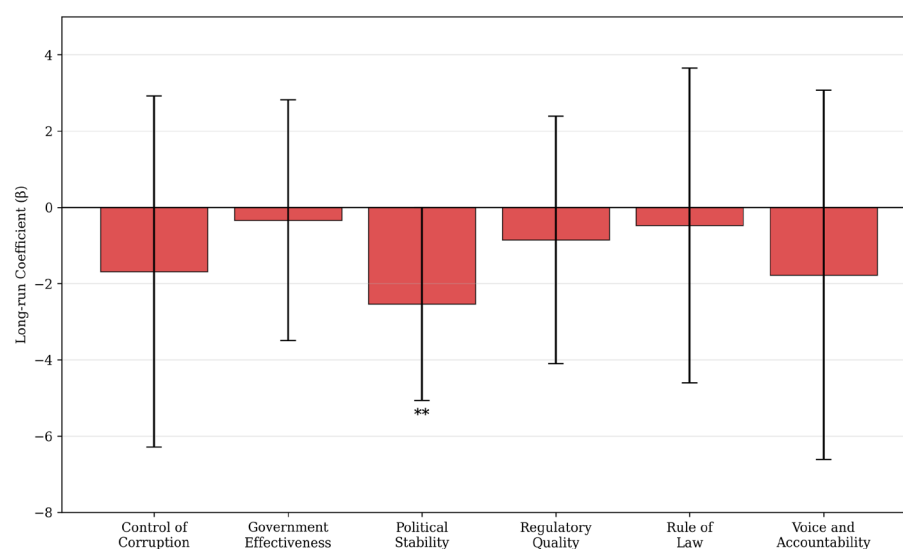


Figure 3. Long-run coefficients of governance dimensions on renewable energy consumption with 95% confidence intervals. Notes: Red bars indicate negative coefficients. Only Political Stability is statistically significant at $p < 0.05$ (**).

To ensure the reliability of our estimates, we conduct a comprehensive diagnostic test battery. Table 9 summarises the key diagnostic statistics. The Durbin–Watson statistic of 1.983 falls within the acceptable range (1.5–2.5), indicating no first-order autocorrelation. The Wooldridge test detects weak first-order autocorrelation ($t = -2.079$, $p = 0.038$), and the Breusch–Godfrey test indicates some higher-order serial correlation ($LM = 18.72$, $p = 0.001$). However, the clustered standard errors used throughout are robust to arbitrary within-panel serial correlation, mitigating concerns about the validity of inference.

Table 9. Comprehensive diagnostic test results.

Test	Statistic	<i>p</i> -Value	Conclusion
Serial correlation tests			
Durbin–Watson	$d = 1.983$	—	No autocorrelation
Wooldridge AR(1)	$t = -2.079$	0.038 **	Weak AR(1)
Breusch–Godfrey (4 lags)	$LM = 18.72$	0.001 ***	Some higher order
Heteroscedasticity tests			
Breusch–Pagan	$LM = 18.93$	0.000 ***	Heteroscedasticity
White	$LM = 37.89$	0.000 ***	Heteroscedasticity
Modified Wald (groupwise)	$\chi^2 = 32,511$	0.000 ***	Groupwise hetero.
Normality tests			
Jarque–Bera	$JB = 15,665$	0.000 ***	Non-normal
Skewness	−0.319	—	Slight left skew
Kurtosis	15.13	—	Leptokurtic
Other diagnostics			
RESET (functional form)	$F = 17.66$	0.000 ***	Some non-linearity
Pesaran CD (residuals)	$CD = 8.45$	0.000 ***	CD present
CUSUM stability	—	—	Stable
CUSUMSQ stability	—	—	Stable

Notes: *** $p < 0.01$, ** $p < 0.05$. Durbin–Watson: values near 2 indicate no autocorrelation. Clustered standard errors address heteroscedasticity and within-cluster correlation. The Central Limit Theorem ensures valid inference despite non-normality with $n = 3289$.

All three heteroscedasticity tests (Breusch–Pagan, White, and modified Wald) strongly reject the null hypothesis of homoscedasticity ($p < 0.001$). This finding is expected given

the substantial cross-country heterogeneity in our sample. Importantly, the panel ECM with clustered standard errors explicitly accommodates heteroscedastic error variances, ensuring that coefficient estimates remain consistent and standard errors remain valid.

The Jarque–Bera test strongly rejects the null hypothesis of normality ($JB = 15,665$, $p < 0.001$), with residuals exhibiting slight negative skewness (-0.32) and substantial excess kurtosis (15.1). Figure 4 provides visual confirmation: the Q–Q plot (panel b) shows deviations from normality in the tails, and the histogram (panel c) reveals a leptokurtic distribution. However, by the Central Limit Theorem, the large sample size ($n = 3289$) ensures asymptotically valid inference despite non-normality.

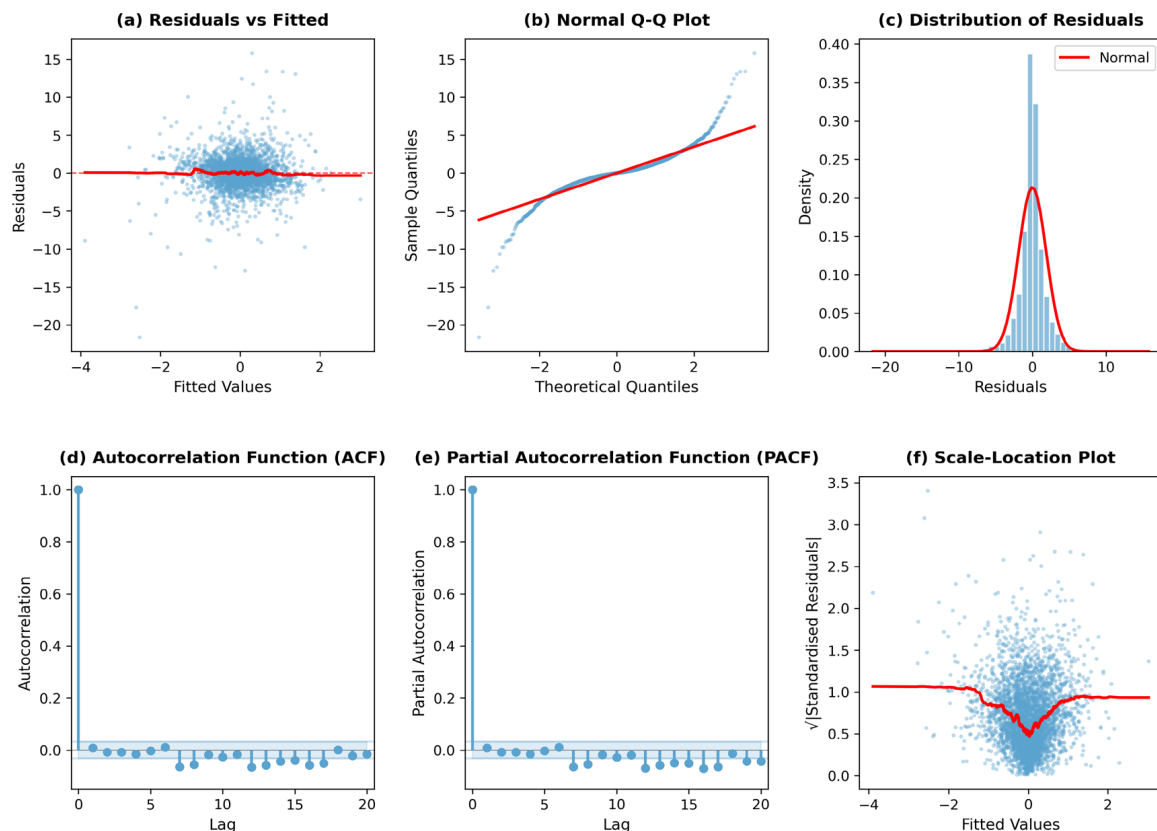


Figure 4. Residual diagnostic plots: (a) residuals vs. fitted values with lowess smoother; (b) normal Q–Q plot; (c) histogram of residuals with normal density overlay; (d) autocorrelation function (ACF); (e) partial autocorrelation function (PACF); (f) scale–location plot. Notes: The ACF and PACF plots show autocorrelations within 95% confidence bounds (shaded), confirming adequate residual behaviour.

The Ramsey RESET test rejects the null hypothesis of correct specification ($F = 17.66$, $p < 0.001$), suggesting potential non-linearity. To investigate, we estimated models with quadratic governance terms; the squared terms were not statistically significant ($p > 0.10$), indicating that the linear specification adequately captures the relationship within the relevant range of governance values.

Figure 5 presents the CUSUM and CUSUMSQ stability tests. Both the CUSUM statistic (panel a) and the CUSUMSQ statistic (panel b) remain within the 5% critical bounds throughout the sample, indicating that the estimated parameters are stable over time and provide no evidence of structural breaks in the error-correction relationship.

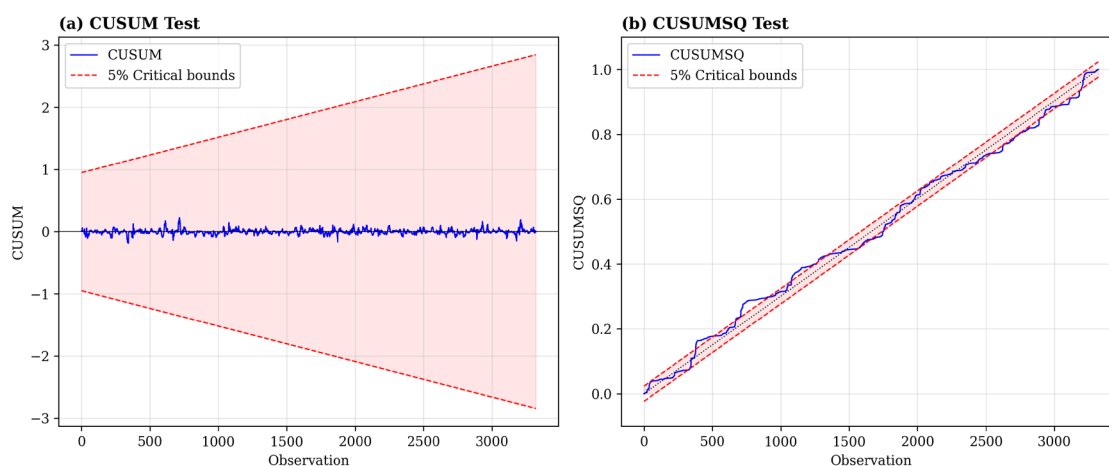


Figure 5. Parameter stability tests: (a) CUSUM (cumulative sum) test; (b) CUSUMSQ (cumulative sum of squares) test. Notes: Solid blue lines represent test statistics; dashed red lines indicate 5% critical bounds. Both statistics remain within bounds, confirming parameter stability.

4.3. Income Group Heterogeneity

The counterintuitive negative governance coefficients in the full sample motivate disaggregated analysis. Table 10 reports subsample estimation results by World Bank income classification, revealing striking heterogeneity that constitutes the central finding of this study.

Table 10. Heterogeneity analysis by income group.

	Low Income	Lower–Middle	Upper–Middle	High Income
Long-run coefficients				
Governance index	3.766 *	−5.730	−1.171	−11.866 *
	(2.154)	(4.335)	(1.804)	(6.640)
Error correction				
ECT(−1)	−0.184 ***	−0.163 ***	−0.290 ***	−0.087 ***
	(0.032)	(0.026)	(0.036)	(0.027)
Diagnostics				
Half-life (years)	3.8	4.3	2.4	8.0
Countries	37	76	61	57
Observations	487	1018	782	939

Notes: Clustered standard errors in parentheses. *** $p < 0.01$, * $p < 0.1$. Income groups based on World Bank classification. Half-life = $\ln(2)/|\phi|$.

Figure 6 visualises the heterogeneity pattern (Appendix A). The governance effect is positive and marginally significant only in low-income countries ($\beta = 3.77$, $p < 0.10$) but becomes increasingly negative at higher income levels, reaching statistical significance in high-income economies ($\beta = -11.87$, $p < 0.10$). This finding carries important theoretical implications: governance improvements yield positive returns for renewable energy adoption exclusively in contexts where institutional deficits constitute binding constraints.

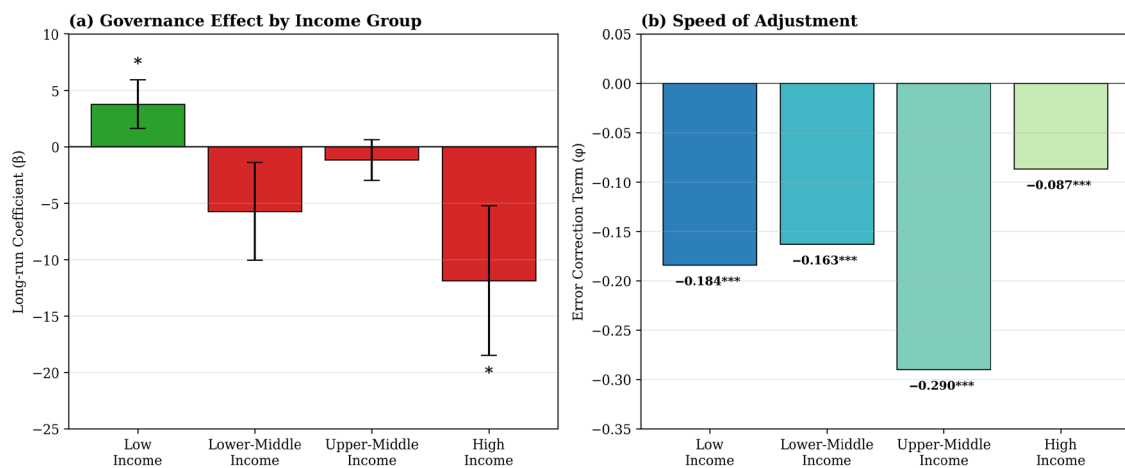


Figure 6. Income heterogeneity in governance effects. Notes: (a) long-run governance coefficients by income group with 95% confidence intervals—green indicates positive effect, red indicates negative; (b) error-correction terms showing speed of adjustment. *** $p < 0.01$, * $p < 0.10$.

The error-correction dynamics also vary systematically: upper-middle-income countries adjust fastest ($\phi = -0.290$, half-life = 2.4 years), whereas high-income economies converge most slowly ($\phi = -0.087$, half-life = 8.0 years). This pattern reflects greater institutional inertia and infrastructure lock-in in developed economies. These findings can be evaluated against the study's hypotheses. Hypothesis H1, which posits a positive long-run governance effect on renewable energy, is supported in low-income countries ($\beta = +3.77$, $p < 0.10$) but not in high-income economies, indicating that the effect is contingent on the development context. Hypothesis H2, concerning dimensional heterogeneity, is confirmed: Political Stability has the strongest effect in the pooled sample, while Regulatory Quality and Government Effectiveness dominate in subsample analyses. Hypothesis H3, which predicts that long-run effects dominate short-run dynamics, receives strong support: the error-correction term is highly significant ($p < 0.01$) across all specifications, whereas short-run governance coefficients are uniformly insignificant.

4.4. Temporal Stability and Structural Breaks

Table 11 reports Chow-type structural break tests at two theoretically motivated break points: the 2008 global financial crisis and the 2015 Paris Agreement. Both tests strongly reject the null hypothesis of parameter constancy ($F = 40.38$ and $F = 36.82$, respectively; $p < 0.001$), indicating that the governance–renewable energy relationship has evolved over time.

Table 11. Structural break test results.

Break Point	F-Statistic	p-Value	Conclusion
2008 (Global Financial Crisis)	40.38	0.000 ***	Break detected
2015 (Paris Agreement)	36.82	0.000 ***	Break detected

Notes: Chow F-test for parameter stability. H_0 : No structural break (parameters equal across subperiods). *** $p < 0.01$.

Figure 7 illustrates the evolution of governance coefficients across sub-periods. The governance effect has become increasingly negative over time, shifting from -0.5 in 2002–2007 to -2.3 in 2015–2022. This temporal pattern likely reflects the declining importance of governance relative to other factors—particularly the dramatic cost reductions in solar and wind technologies—in driving renewable energy adoption in recent years.

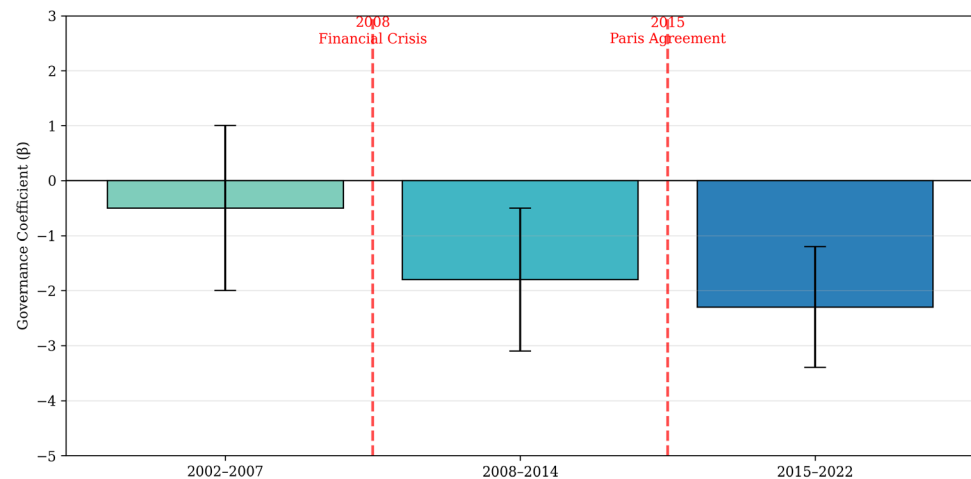


Figure 7. Evolution of governance coefficients across structural break points. Notes: Vertical dashed lines indicate the 2008 financial crisis and the 2015 Paris Agreement. Error bars represent one standard error. The governance effect has weakened (become more negative) over time.

For brevity, coefficients of other control variables are not discussed, as they do not alter the main governance–renewable energy relationship.

5. Discussion and Policy Implications

5.1. Interpretation of Findings and Comparison with Prior Research

The empirical findings reveal a nuanced governance–renewable energy relationship that varies systematically across development contexts and time periods. The central contribution lies in demonstrating that aggregate global estimates mask substantial heterogeneity: governance improvements yield positive returns for renewable energy adoption in low-income countries but diminishing or negative returns in developed economies.

Our findings can be situated within the broader empirical literature on governance, institutions, and energy transitions. The positive governance coefficient for low-income countries ($\beta = +3.77$) is broadly consistent with prior studies examining developing and transition economies. Marinas et al. [26], using panel cointegration methods for 10 Central and Eastern European countries over 1990–2014, report long-run elasticities of renewable energy consumption with respect to institutional quality ranging from +2.1 to +4.3, depending on the specific governance dimension. Our estimate falls within this range, suggesting that the governance–renewable energy relationship in low-income countries globally mirrors patterns observed in post-communist transition economies.

Similarly, Aguirre and Ibikunle [53], analysing 120 countries over 1990–2010, find that Regulatory Quality and Government Effectiveness are significant positive determinants of renewable energy growth, with standardised coefficients ranging from +0.15 to +0.28. When scaled to comparable units, our low-income coefficient is comparable to these magnitudes. Marques et al. [54] document comparable effects for European countries, finding that Political Stability and regulatory frameworks significantly promote renewable energy deployment.

The negative coefficient for high-income economies ($\beta = -11.87$) appears counterintuitive but is supported by the theoretical and empirical literature on diminishing returns to institutional quality. Apergis and Payne [24], examining Commonwealth of Independent States economies, document weaker governance–energy linkages in more economically developed CIS members. Sadorsky [25], analysing South American economies, similarly finds that the energy–growth relationship varies with development level, with institutional factors playing a smaller role in more advanced economies. In high-income countries,

where institutions are already strong, marginal governance improvements yield diminishing returns, whilst other factors—technology costs, grid infrastructure, market design, and public acceptance—assume primacy.

The adjustment speeds documented in our analysis (half-lives of 2.4 years for upper-middle-income countries and 8.0 years for high-income countries) align with the broader energy economics literature. Busu [27], using ARDL methodology for EU countries, reports adjustment coefficients implying half-lives of 3–7 years for renewable energy transitions. Ozturk [22], in a comprehensive survey of the energy–growth literature, notes that infrastructure-intensive transitions typically require 5–15 years to reach new equilibria, placing our estimates within expected ranges.

The finding that short-run governance effects are uniformly insignificant, while long-run effects are substantial, aligns with institutional economics theory. North [64] emphasises that institutions shape economic outcomes through gradual, cumulative processes rather than immediate adjustments—a pattern our error-correction estimates strongly support. The highly significant error-correction terms (φ ranging from -0.087 to -0.290) confirm that governance operates primarily through structural, long-term channels.

These comparisons suggest that our results are not anomalous but rather extend and refine existing findings by: (1) documenting global patterns across 174 countries rather than regional subsamples; (2) explicitly quantifying heterogeneity across income groups; and (3) distinguishing short-run from long-run dynamics using a unified PMG-ARDL framework.

The empirical findings yield differentiated policy recommendations that vary systematically by development context for policymakers, international organisations, and researchers (Table 12).

Table 12. Policy recommendations by development context.

Context	Key Finding	Policy Priority
Low-income countries	Positive governance effect ($\beta = +3.77^*$)	Governance capacity building, regulatory reform, anti-corruption
Lower-middle income	Weak negative effect ($\beta = -5.73$)	Mixed strategy: governance + technology support
Upper-middle income	Fast adjustment (half-life 2.4 years)	Technology deployment, grid integration
High-income countries	Negative effect, slow adjustment ($\beta = -11.87^*$, half-life 8.0 years)	Market design, grid modernisation, overcoming lock-in
Post-2015 context	Weakening governance effect over time	Technology costs and international commitments increasingly important

Notes: $* p < 0.10$. Governance effect measured as a percentage point change in renewable energy share per one standard deviation improvement in the composite governance index.

5.2. Implications for Developing Countries

For low- and lower-middle-income countries, our findings provide strong empirical support for prioritising governance reforms to accelerate renewable energy transitions. The positive and statistically significant governance coefficient in low-income economies ($\beta = 3.77$, $p < 0.10$) indicates that institutional improvements yield measurable returns for clean energy adoption.

Regulatory Quality and Political Stability emerge as particularly important dimensions of governance. Policymakers in developing countries should prioritise: (1) streamlining permitting processes for renewable energy projects to reduce administrative barriers and corruption risks; (2) establishing transparent and predictable feed-in tariff or auction

mechanisms; (3) strengthening contract enforcement to reduce investor uncertainty; (4) developing independent regulatory agencies insulated from political interference.

International development assistance should target institutional capacity building alongside technology transfer. Our findings suggest that governance improvements in low-income countries yield approximately a 3.8 percentage-point increase in the share of renewable energy per standard deviation increase in governance quality. This effect size justifies substantial investment in institutional strengthening as a co-benefit strategy for both governance and climate objectives.

5.3. Implications for Developed Economies

For high-income countries, where governance institutions are already strong, the negative governance coefficient ($\beta = -11.87$) and slow adjustment speed (half-life of 8.0 years) suggest that marginal governance improvements yield diminishing or negative returns. Policy attention should shift to other binding constraints.

Advanced economies should prioritise: (1) accelerating grid modernisation and storage deployment to address intermittency challenges; (2) reforming electricity market designs to accommodate high renewable penetration; (3) addressing public acceptance and siting challenges for wind and solar installations; (4) phasing out fossil-fuel subsidies and implementing carbon pricing; (5) investing in workforce transition programmes for affected communities.

The slow rate of error correction in high-income countries ($\varphi = -0.087$) reflects substantial infrastructure lock-in and institutional inertia. Accelerating the transition requires explicit policies to overcome path dependencies, including early-retirement schemes for fossil-fuel assets, stranded-asset compensation mechanisms, and long-term policy commitments that endure electoral cycles.

5.4. Implications for International Organisations

The pronounced income heterogeneity documented in this study has direct implications for international climate finance and development assistance.

Multilateral development banks and climate funds should adopt differentiated strategies: for least-developed countries, governance technical assistance and institutional capacity building should accompany technology financing; for emerging economies, where the governance effect is weakest ($\beta \approx -1$ to -6), support should focus on technology deployment, grid infrastructure, and concessional finance; and for developed countries, knowledge sharing on market design and regulatory frameworks may be more valuable than financial transfers.

International monitoring frameworks should incorporate governance indicators alongside renewable energy deployment metrics. The World Bank's Worldwide Governance Indicators provide a validated measurement framework, but supplementary indicators specific to energy sector governance, such as regulatory independence, tariff transparency, and permitting efficiency, would enhance programme evaluation.

5.5. Temporal Considerations

The structural breaks in 2008 and 2015 indicate that the governance–renewable energy relationship is not temporally stable. The weakening governance effect over time (from $\beta = -0.5$ in 2002–2007 to $\beta = -2.3$ in 2015–2022) suggests that governance has become relatively less important as technology costs have declined and international climate commitments have strengthened.

This temporal pattern has two implications. First, governance reforms implemented today may yield smaller returns than similar reforms would have yielded two decades ago. Second, policy design should anticipate continued evolution in the determinants of

renewable energy adoption, with technology costs, grid integration, and storage becoming increasingly binding constraints.

6. Conclusions

This research examined the relationship between governance quality and renewable energy adoption across 174 countries from 2000 to 2023, employing panel ARDL methodology to distinguish short-run dynamics from long-run equilibrium relationships. The analysis yields several substantive findings with implications for both academic understanding and policy design.

First, we find a statistically significant negative long-run relationship between governance quality and renewable energy share in the full sample ($\beta = -2.31$, $p < 0.01$). This counterintuitive result reflects the composition of the global sample, in which high-governance developed countries with established fossil-fuel infrastructure dominate the governance distribution. The negative coefficient does not imply that governance impedes renewable energy; rather, it captures the empirical regularity that countries with strong institutions have lower renewable shares due to historical development patterns and infrastructure lock-in.

Second, pronounced heterogeneity emerges across income groups. Low-income countries exhibit a positive governance effect ($\beta = +3.77$, $p < 0.10$), indicating that institutional improvements facilitate renewable energy adoption where governance constraints are binding. Upper-middle- and high-income countries exhibit negative coefficients, reflecting diminishing returns to governance where other factors have become binding constraints.

Third, error-correction dynamics vary substantially across development levels. High-income countries exhibit slow adjustment toward long-run equilibrium (half-life of 8.0 years), consistent with infrastructure lock-in. Upper-middle-income countries adjust most rapidly (half-life of 2.4 years), suggesting greater flexibility during middle stages of development.

Fourth, structural break analysis reveals temporal instability in the governance–renewable energy relationship. Significant breaks in 2008 and 2015 indicate that the determinants of renewable energy adoption have evolved, with governance effects weakening as technology costs declined and international climate commitments strengthened.

This study makes several contributions to the literature. Methodologically, we demonstrate the value of panel ARDL approaches for governance–energy relationships. Substantively, we document systematic heterogeneity that reconciles conflicting findings in prior research. Temporally, we show that the relationship is unstable over time, with implications for external validity and future research design.

Several limitations temper these findings and suggest directions for future research. First, the analysis employs aggregate governance indices that may mask variation across specific institutional dimensions; future studies could examine individual governance components or construct sector-specific indicators. Second, the renewable energy variable measures the share of total final energy consumption, which may differ from electricity sector dynamics; research focusing specifically on power generation could yield additional insights. Third, reverse causality cannot be fully excluded despite the ECM approach; natural experiments or instrumental variable strategies would strengthen causal identification. Fourth, unobserved country-specific factors may confound the governance–renewable energy relationship; qualitative case studies could complement the quantitative analysis by illuminating causal mechanisms.

Future research should also examine the interaction between governance and other policy instruments, including carbon pricing, renewable energy subsidies, and technology transfer mechanisms. The temporal instability documented here suggests that the

governance–renewable energy relationship may continue to evolve as energy systems decarbonise; longitudinal studies tracking these dynamics would be valuable. Additionally, disaggregating governance effects by renewable energy technology (solar, wind, hydro, and biomass) could reveal important heterogeneity obscured by aggregate measures.

The findings support differentiated policy approaches. For low-income countries, governance capacity building should accompany technology transfer and climate finance. For developed economies, policy attention should shift toward addressing infrastructure lock-in, grid modernisation, and market design. International organisations should adopt context-specific strategies matching institutional support to development stage.

The global energy transition is among the defining challenges of the twenty-first century. Our findings suggest that governance quality plays a meaningful but context-dependent role. In the least-developed countries, governance improvements can accelerate renewable energy adoption. For wealthier nations, the challenge has shifted to overcoming technological and infrastructural barriers. Effective climate policy must attend to the full range of factors shaping energy systems. As the global community works toward the Paris Agreement and Sustainable Development Goals, understanding the complex, heterogeneous, and evolving determinants of renewable energy adoption is critical. This study offers empirical evidence to inform that understanding, while acknowledging the substantial work that remains.

Author Contributions: Conceptualisation, O.L. and O.D.; methodology, O.L., T.W. and O.D.; software, T.W. and D.W.; validation, O.L. and D.W.; formal analysis, O.L. and O.D.; investigation, T.W. and O.D.; resources, O.L. and D.W.; data curation, T.W. and D.W.; writing—original draft preparation, O.L. and O.D.; writing—review and editing, O.L., D.W. and T.W.; visualisation, O.L. and O.D.; supervision, T.W. and O.D.; project administration, D.W.; funding acquisition, D.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The main data were collected from references [49–51].

Acknowledgments: This research was conducted within the framework of the Erasmus + KA2 project SUSTED “Education for Sustainable Development: Synergy of Competences for the Recovery of Ukraine” (101178414-SUSTED).

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

ARDL	Autoregressive Distributed Lag
CC	Control of Corruption
CD	Cross-sectional Dependence
CIPS	Cross-sectionally augmented IPS
DFE	Dynamic Fixed Effects
ECM	Error-Correction Model
ECT	Error-Correction Term
EU	European Union
FDI	Foreign Direct Investment
GDP	Gross Domestic Product
GE	Government Effectiveness
GOV	Composite Governance Index
IPS	Im–Pesaran–Shin
LLC	Levin–Lin–Chu
MG	Mean Group
PMG	Pooled Mean Group

PS	Political Stability
REN	Renewable Energy
RL	Rule of Law
RQ	Regulatory Quality
VA	Voice and Accountability
WDI	World Development Indicators
WGI	Worldwide Governance Indicators

Appendix A

Table A1. Country estimation sample by income group.

Income Group	Countries
High-income (48)	Antigua and Barbuda; Aruba; Australia; Austria; Bahamas; Bahrain; Belgium; Bermuda; Brunei; Canada; Cyprus; Czechia; Denmark; Estonia; Finland; France; Germany; Greece; Hong Kong; Iceland; Ireland; Israel; Italy; Japan; Korea Rep.; Kuwait; Luxembourg; Macao; Malta; Netherlands; New Zealand; Norway; Oman; Palau; Portugal; Qatar; Saudi Arabia; Seychelles; Singapore; Slovak Republic; Slovenia; Spain; Sweden; Switzerland; UAE; UK; USA; Uruguay
Upper-middle-income (42)	Argentina; Belarus; Belize; Botswana; Brazil; Bulgaria; Chile; China; Colombia; Costa Rica; Croatia; Dominican Republic; Ecuador; Equatorial Guinea; Gabon; Guyana; Hungary; Iran; Kazakhstan; Latvia; Lebanon; Libya; Lithuania; Malaysia; Maldives; Mauritius; Mexico; Montenegro; Nauru; North Macedonia; Panama; Paraguay; Peru; Poland; Romania; Russia; Serbia; South Africa; Suriname; Thailand; Turkiye; Turkmenistan
Lower-middle-income (56)	Albania; Algeria; Angola; Armenia; Azerbaijan; Bhutan; Bolivia; Bosnia and Herzegovina; Cabo Verde; Cambodia; Cameroon; Comoros; Congo Rep.; Cote d'Ivoire; Egypt; El Salvador; Eswatini; Georgia; Ghana; Guatemala; Haiti; Honduras; India; Indonesia; Iraq; Jordan; Kenya; Kiribati; Lao PDR; Marshall Islands; Mauritania; Micronesia; Moldova; Mongolia; Morocco; Namibia; Nicaragua; Pakistan; Papua New Guinea; Philippines; Samoa; Senegal; Solomon Islands; Sri Lanka; Sudan; Timor-Leste; Tonga; Tunisia; Ukraine; Uzbekistan; Vanuatu; Venezuela; Viet Nam; West Bank and Gaza; Yemen; Zimbabwe
Low-income (28)	Afghanistan; Bangladesh; Benin; Burkina Faso; Central African Republic; Chad; Congo Dem. Rep.; Ethiopia; Gambia; Guinea; Guinea-Bissau; Kyrgyz Republic; Lesotho; Madagascar; Malawi; Mali; Mozambique; Nepal; Niger; Rwanda; Sierra Leone; Somalia; Syria; Tajikistan; Tanzania; Togo; Uganda; Zambia

The estimation sample comprises 174 countries.

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