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Architecting Ecological Resilience: The Impact of Renewable Energy Consumption on Environmental Sustainability (1990–2023)

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Abstract
This paper examines the multi-dimensional nexus between disaggregated renewable energy consumption and environmental sustainability across 29 nations spanning the period 1990–2023. It focuses on whether technology-specific clean energy vectors encompassing solar, wind, hydro, and biofuel sources interact with macroeconomic and institutional catalysts to support carbon mitigation in an integrated framework bridging advanced OECD markets and major emerging giants. Utilizing a balanced panel dataset, the study models carbon dioxide (CO2) emissions against economic scale effects, credit allocation structures, and human capabilities. Advanced second-generation panel estimators that explicitly address pervasive cross-sectional dependence, cointegration, and structural slope heterogeneity, alongside heterogeneous panel causality tests, are deployed to identify dynamic long-run steady states and causal directionality. Findings from the Cross-Sectionally Augmented ARDL (CS-ARDL) approach indicate that aggregate and disaggregated renewable energies, alongside public environmental research and development (R&D) expenditures and human development, exert a statistically significant mitigating impact on carbon emissions. Conversely, economic growth persists as a major structural driver of pollution, while financial development exhibits general statistical neutrality due to "environmentally blind" credit allocation. Policy implications call for immediate, targeted financial subsidies for green R&D in the short run, long-term human capital accumulation, and urgent integration of environmental, social, and governance (ESG) criteria into banking sector financing.

Keywords: Renewable energy consumption, Environmental sustainability, Eco-innovation, Second-generation panel econometrics, CS-ARDL

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1. Introduction

The global shift toward renewable energy is a fundamental structural transformation aimed at resolving the acute conflict between economic expansion and environmental sustainability. While clean infrastructure driven by innovative research and development (R&D) creates a systemic break from polluting paradigms (Han et al., 2025; Wang et al., 2025), policymakers face a complex "double-edged sword" regarding macroeconomic catalysts. Financial development often fuels carbon-intensive activities through 'environmentally blind' credit, and human development gains frequently deepen the environmental footprint. Existing empirical literature struggles to decode this nexus due to significant methodological limitations. Many prior studies employ truncated timeframes (Tariq et al., 2022), analyze heterogeneous samples that mix non-comparable economies (Derindag et al., 2023), or rely on first-generation panel estimators that ignore cross-sectional dependence (CSD) - an assumption frequently violated in highly integrated global economies. Furthermore, previous research often examines energy substitution (Khan, Khan, et al., 2022) or technological innovation (Feng, 2022) in isolation, failing to capture the macro-system's full interdependencies.

To address these critical gaps, this study makes three distinct methodological and empirical contributions to the environmental economics literature. First, it introduces unprecedented methodological rigor by deploying advanced second-generation panel econometrics - specifically the Cross-Sectionally Augmented ARDL (CS-ARDL) estimator and Dumitrescu & Hurlin (2012) causality tests - to explicitly resolve pervasive cross-sectional dependence, structural slope heterogeneity, and endogeneity. Second, it leverages a comprehensive sample and temporal depth, utilizing a balanced panel of 29 nations that uniquely bridges advanced OECD members and major emerging markets over an extended period (1990–2023), thereby providing robust external validity and accounting for recent macro-environmental shifts. Third, it constructs a disaggregated integrated framework; unlike broad aggregate studies, we deconstruct renewable energy into technology-specific vectors (solar, wind, hydro, and biofuel) and model them simultaneously against economic scale, credit allocation structures, human capabilities, and state-led eco-innovation to uncover complex structural anomalies.

Accordingly, this paper empirically tests whether disaggregated clean energy sources and green R&D significantly mitigate long-run CO2 emissions, and whether economic growth persists as the primary pollution driver. It also investigates if financial development exhibits statistical neutrality due to flawed credit allocation, and if long-term human capital accumulation acts as a structural catalyst for ecological resilience. The remainder of the paper is organized as follows: Section 2 critically reviews the literature; Section 3 details the data and second-generation methodology; Section 4 presents the empirical and causality results; Section 5 provides concrete economic interpretations; and Section 6 concludes with targeted policy implications.

2. Literature review

The empirical deconstruction of the macroeconomic matrix governing environmental sustainability requires a profound understanding of how technological, institutional, and financial catalysts interact with global production paradigms. Over past decades, a rich body of scholarship has emerged to trace the shifting frontiers of global pollution. However, a critical review of this literature reveals a fragmented landscape characterized by conflicting empirical outcomes rather than a universal consensus. Most historical studies treat macro-variables in isolation, leading to overlapping conclusions and omitted variable biases. To establish a more critical synthesis and

highlight existing research gaps, this section thematizes the scholarly debate into three interconnected macro-dynamics: the energy-trade nexus, the human welfare paradox, and the financial-technological-institutional triad.

2.1. The renewable energy transition, globalization and structural rebound effects

While the inverse correlation between renewable energy adoption and carbon emissions is theoretically established, empirical evidence demonstrates deep structural contradictions based on regional contexts. Studies in advanced economies (Han et al., 2025; Wang et al., 2025) confirm that clean infrastructure directly drives green growth. However, this optimistic narrative is heavily contested by findings in developing and emerging contexts. For instance, (Mohamud & Mohamud, 2023) and (Tariq et al., 2022) argue that in lower-income and South Asian nations, the deployment of renewables is completely neutralized by consumption-driven "rebound effects" and deeply entrenched structural reliance on fossil fuels. This contradiction is starkly mirrored in the globalization and trade literature. While (Ahmed & Le, 2020) find that technology-driven globalization diminishes carbon intensity, (Wang et al., 2025) and (Ibrahim & Ajide, 2021) highlight a dual ecological outcome: trade liberalization curtails emissions in advanced OECD economies through green technology transfer but exacerbates pollution in developing nations. This conflicting body of evidence exposes a critical methodological flaw in prior studies: imposing broad, systematic generalizations across differing income levels without accounting for structural threshold effects yields precarious and misleading policy recommendations (Derindag et al., 2023).

2.2. The paradox of human development and welfare trajectories

The relationship between human development and environmental sustainability presents a fundamental empirical paradox: does rising welfare inherently necessitate ecological degradation? Scholars like (van den Bergh & Botzen, 2018) advocate for replacing GDP with the Human Development Index (HDI) to lower carbon footprints. Conversely, critical assessments by (Hickel, 2020) and (Xu & Zhao, 2023) reveal a structural trap, demonstrating that human development gains particularly in consumption-driven, middle-income nations often incur unsustainable ecological costs. To reconcile this, recent literature points to the mediating role of education. While (Kızılkaya et al., 2024) view education as a critical enabler of sustainability, (Ritu & Kaur, 2023) find that human capital accumulation initially expanded the ecological footprint in India before post-2020 renewable energy adoption mitigated the impact. This implies that human advancement alone cannot ensure sustainability without concurrent technological leapfrogging (Polat & Çil, 2024), highlighting a gap in understanding how human capital directly interacts with specific, disaggregated clean energy vectors.

2.3. The financial-technological-institutional triad

A major shortcoming in existing literature is the artificial separation of financial development, technological innovation, green finance, and governance into distinct analytical silos, despite their profound practical overlap. The literature consistently portrays financial development as a "double-edged sword." (Majeed & Mazhar, 2019) and (Nathaniel et al., 2024) observe that financial deepening fosters sustainability in OECD economies through ESG prioritization but dramatically deteriorates the ecological footprint in developing nations due to "environmentally blind" credit

expansion. The critical determinant explaining this contradiction is the institutional and technological environment.

Innovation literature confirms that R&D investments only decouple economic growth from emissions if they surpass specific GDP thresholds (Karimi Alavijeh & Zangoei, 2023; Fan et al., 2025). Moreover, the success of green finance mechanisms - such as green bonds and carbon markets (Bilal & Shaheen, 2024; L. Tan et al., 2025) - is strictly contingent upon robust institutional governance and political stability (Udeagha & Ngepah, 2023). As (Wen et al., 2022) and (Gyimah et al., 2026) unequivocally assert, financial sector expansion reduces emissions solely under strong governance; in institutionally fragile settings, it inadvertently acts as a pollution catalyst. Therefore, studying these elements independently fails to capture the complex, conditional nature of environmental macroeconomics.

2.4. Identification of research gaps

Synthesizing this scholarly debate exposes three critical research gaps that this study aims to fill. First, an integration gap: prior research largely fails to simultaneously model the financial-technological-institutional triad, leading to a fragmented understanding of how "environmentally blind" credit and state-led eco-innovation interact within the same framework. Second, an aggregation bias: the majority of studies treat renewable energy as a monolithic variable, obscuring the unique mitigative capacities and potential rigidities (e.g., biofuels vs. solar) of specific clean energy technologies. Third, a methodological gap: most historical panel studies in this domain rely on first-generation estimators that assume cross-sectional independence. In a highly globalized era characterized by interconnected financial systems and trade spillovers, ignoring cross-sectional dependence (CSD) generates biased and spurious inferences. By deploying the advanced CS-ARDL framework and disaggregating renewable energy sources across a balanced advanced-emerging panel, this study rigorously bridges these unresolved gaps.

3. Empirical methodology

Spanning the 1990–2023 period, this study utilizes a balanced panel dataset of 29 nations (Argentina, Australia, Austria, Belgium, Brazil, Canada, China, Denmark, Finland, France, Germany, Hungary, India, Indonesia, Ireland, Italy, Japan, Malaysia, the Netherlands, Norway, Portugal, Singapore, South Africa, Spain, Sweden, Switzerland, Thailand, the United Kingdom, and the United States). The deliberate selection of this specific cohort over other economies is driven by three rigorous criteria: (1) Data Continuity: The uninterrupted historical availability of specific variables - particularly disaggregated renewable energy vectors and green R&D metrics - which is essential for robust balanced panel estimations; (2) Global Scale: Bridging advanced OECD members and major emerging markets uniquely captures the world's largest carbon emitters and eco-innovators, ensuring high external validity; and (3) Transition Maturity: Excluding institutionally fragile nations or those with negligible renewable adoption effectively prevents extreme statistical distortions, yielding highly precise and generalizable parameters.

3.1. Study variables

Drawing upon contemporary empirical literature and the structural characteristics of the selected cross-country panel, this study develops a rigorous econometric framework designed to address the central research question. To capture the multi-dimensional environmental facets of sustainable development, Carbon Dioxide (CO_2) emissions are utilized as the focal dependent variable. The

comprehensive selection of explanatory and macro-structural control variables, alongside their respective codes, precise units of measurement, and institutional data repositories, are systematically detailed in Table 1. This baseline matrix encompasses critical environmental vectors - specifically disaggregated and aggregate renewable energy consumption - integrated with core macroeconomic determinants including Gross Domestic Product (GDP), trade openness, the KOF globalization index (KOFGI), financial development (FIN), the Human Development Index (HDI), public and private eco-innovation expenditures (RDERET), and secondary educational attainment (SEC) as a proxy for human capital accumulation. To preclude potential multicollinearity complications that could inherently arise from incorporating highly collinear energy metrics into a single baseline specification, the environmental implications of each individual clean energy source are estimated within separate, disaggregated empirical equations. Ultimately, this isolated methodological configuration facilitates a highly precise evaluation of how distinct renewable energy profiles, synchronized with vital institutional and economic covariates, uniquely dictate the trajectory of global carbon emissions over the 1990–2023 temporal horizon.

Table 1- Study variables and data sources

Code	Variable	Unit of Measurement	Source
CO2	Carbon Dioxide Emissions	Total CO2 emissions (Million tonnes)	Our World in Data (GitHub)
SOLAR	Solar Energy Consumption	Primary energy consumption from solar sources (Terawatt-hours, TWh)	Our World in Data (GitHub)
WIND	Wind Energy Consumption	Primary energy consumption from wind sources (Terawatt-hours, TWh)	Our World in Data (GitHub)
HYDRO	Hydroelectric Energy Consumption	Primary energy consumption from hydropower sources (Terawatt-hours, TWh)	Our World in Data (GitHub)
BIOFUEL	Biofuel Energy Consumption	Primary energy consumption from biofuel sources (Terawatt-hours, TWh)	Our World in Data (GitHub)
TOT_REN	Total Renewable Energy Consumption	Total primary energy consumption from renewable sources (Terawatt-hours, TWh)	Our World in Data (GitHub)
GDP	Gross Domestic Product	Constant 2010 US Dollars (USD)	World Development Indicators (WDI)
TRAND	Trade Openness	Total trade volume as a percentage (%) of GDP	World Development Indicators (WDI)
KOFGI	Globalization Index	Composite index score (0–100)	KOF Swiss Economic Institute
FIN	Financial Development	Domestic credit provided to the private sector (% of GDP)	World Development Indicators (WDI)
HDI	Human Development Index	Composite index score (0–1)	Our World in Data / UNDP
SEC	Educational Attainment	Gross secondary school enrollment ratio (%)	World Development Indicators (WDI)
RDERET	Renewable Energy R&D Expenditures	Public/Private R&D expenditures in constant 2010 US Dollars (USD)	OECD Data Explorer

$$\textit{Model 1}: CO2_{i,t} = f\left(GDP_{i,t} + FIN_{i,t} + HDI_{i,t} + RDERET_{i,t} + SOLAR_{i,t}\right) \quad (1)$$

$$\textit{Model 2}: CO2_{i,t} = f\left(GDP_{i,t} + FIN_{i,t} + HDI_{i,t} + RDERET_{i,t} + WIND_{i,t}\right) \quad (2)$$

$$\textit{Model 3}: CO2_{i,t} = f\left(GDP_{i,t} + FIN_{i,t} + HDI_{i,t} + RDERET_{i,t} + HYDRO_{i,t}\right) \quad (3)$$

$$\textit{Model 4}: CO2_{i,t} = f\left(GDP_{i,t} + FIN_{i,t} + HDI_{i,t} + RDERET_{i,t} + BIOFUEL_{i,t}\right) \quad (4)$$

$$\textit{Model 5}: CO2_{i,t} = f\left(GDP_{i,t} + FIN_{i,t} + HDI_{i,t} + RDERET_{i,t} + TOT_REN_{i,t}\right) \quad (5)$$

3.1.1. Carbon dioxide (CO_2) emissions

Carbon dioxide (CO_2) emissions, predominantly generated through fossil fuel combustion, industrial processes, and deforestation, constitute the primary driver of anthropogenic climate change (Friedlingstein et al., 2022). Although CO_2 is not conventionally classified as a direct respiratory toxicant like particulate matter or sulfur dioxide, it indirectly exacerbates air pollution; the rising global temperatures induced by prolonged CO_2 accumulation intensify the photochemical formation of urban smog and systematically degrade overall air quality (Jacob & Winner, 2009). As the most prevalent greenhouse gas, CO_2 traps solar radiation within the atmosphere, accelerating the greenhouse effect and precipitating severe ecological anomalies, including melting ice caps, sea-level rise, and an increased frequency of extreme weather events. Consequently, because these profound climatic shifts pose severe threats to global agricultural systems and vulnerable human societies, the structural reduction of CO_2 emissions has emerged as the indispensable focal point of contemporary environmental mitigation policies (Shahbaz & Sinha, 2019).

3.1.2. Renewable energy consumption

Renewable energy consumption encompassing solar, wind, and hydro power serves as a critical macro-environmental indicator measured quantitatively in terawatt-hours or total energy shares (REN21, 2021). This transition actively stimulates economic growth by cutting fossil fuel imports and generating new industrial employment opportunities (IEA, 2020). While continuous technological progress and economies of scale have drastically driven down production costs, targeted public policies and subsidies remain essential to catalyze widespread adoption. Beyond immediate carbon abatement, expanding clean energy portfolios fortifies national energy security by insulating economies from volatile global fuel markets and mitigating associated geopolitical risks (World Bank Group, 2021). Consequently, higher renewable energy utilization serves as a definitive benchmark of a nation's technological integration and its structural commitment to global sustainable development goals (Hezla et al., 2025).

3.1.3. Gross Domestic Product (GDP)

Gross Domestic Product (GDP) quantifies the aggregate market value of all final goods and services produced within a nation's borders during a specific timeframe, serving as the primary benchmark for macroeconomic performance (Fleurbaey, 2009). Methodologically, GDP is evaluated through three theoretically equivalent accounting frameworks production (sectoral value-added), income (total domestic earnings), and expenditure (final consumption, investment, government spending, and net exports) and can be expressed as either nominal value or inflation-adjusted real GDP (van den Bergh, 2009). Despite its widespread adoption, empirical literature

increasingly highlights that GDP is an imperfect proxy for societal welfare. Critically, standard GDP metrics fail to account for income inequality, non-market transactions, and the severe externalities of economic expansion, such as environmental degradation and natural resource depletion, which necessitates its cautious integration into sustainable development models (Costanza et al., 2014).

3.1.4. Trade openness

Trade openness denotes the structural integration of a domestic economy into international markets, conventionally operationalized as the aggregate volume of exports and imports relative to Gross Domestic Product (GDP) (Frankel & Romer, 2017). Proponents argue that market liberalization drives economic efficiency, stimulates long-term growth, and elevates living standards by exposing domestic enterprises to foreign competition and leveraging comparative advantages (Dollar & Kraay, 2004). Conversely, empirical literature cautions against the attendant vulnerabilities of hyper-integration, including heightened susceptibility to volatile global macroeconomic shocks, structural challenges for nascent domestic industries, and widened social inequalities (Goldberg & Pavcnik, 2007). Ultimately, a nation's trade trajectory is not merely an isolated policy variable but is deeply mediated by exogenous dynamics, such as geographic location, natural resource endowments, technological capacities, and institutional quality.

3.1.5. Globalization Index

The Globalization Index, most notably the KOF index, is a composite metric that quantifies a nation's multi-dimensional global integration across economic, social, and political dimensions (Dreher, 2006). It evaluates de facto actual interactions, such as trade and foreign direct investment, alongside de jure institutional frameworks, including tariffs and capital restrictions (Gygli et al., 2019). While widely utilized in macro-econometric modeling to capture international interconnectedness, empirical literature cautions that a singular index inherently simplifies a highly multifaceted phenomenon, requiring nuanced interpretation when assessing its ecological and developmental impacts (Potrafke, 2015).

3.1.6. Financial development

Financial development denotes the structural expansion, diversification, and regulatory advancement of a country's financial system, typically proxied by domestic credit to the private sector (King & Levine, 1993). While deep financial markets mobilize capital, ease credit access, and stimulate economic investments, unmonitored credit growth poses severe systemic risks, including asset bubbles and non-performing loans (Schularick & Taylor, 2012). Therefore, sound financial deepening relies profoundly on institutional quality and rigorous risk management to maintain macroeconomic stability and ensure that credit expansion productively drives sustainable development rather than triggering financial crises (Levine, 2005).

3.1.7. Human Development Index (HDI)

The Human Development Index (HDI) is a composite statistical metric designed to evaluate national achievements across three core dimensions: health (life expectancy at birth), knowledge (mean and expected years of schooling), and standard of living (GNI per capita) (Anand & Sen, 2003). Conceptually rooted in Amartya Sen's capability approach and pioneered by Mahbub ul Haq, the index successfully shifts the macroeconomic paradigm from pure income expansion to holistic human well-being (Sagar & Najam, 1998). Ranging from 0 to 1, the HDI facilitates standardized cross-country welfare comparisons, though contemporary empirical literature increasingly cautions

against its inherent structural limitations, particularly its omission of ecological sustainability and internal distributional equity (Neumayer, 2001).

3.1.8. Renewable energy R&D expenditures

Renewable energy research and development (R&D) expenditures represent the aggregate public and private financial resources allocated to innovate, optimize, and deploy clean energy technologies, spanning solar photovoltaics, wind power, biomass, and advanced energy storage systems (Garrone & Grilli, 2010). Empirical literature demonstrates that targeted R&D funding is paramount for overcoming structural technical bottlenecks, expanding economies of scale, and systematically driving down production costs (Popp, 2002). Within this innovation ecosystem, state-led public R&D investments effectively mitigate initial high-risk capital barriers, thereby establishing a baseline that catalyzes private sector commercial innovation and patent development (Johnstone et al., 2009). Ultimately, sustained R&D expenditure acts as a critical macroeconomic catalyst, transforming grid reliability and accelerating the structural transition toward carbon-neutral energy systems.

3.1.9. Educational attainment (secondary enrollment)

Educational attainment, typically proxied by the Gross Enrollment Ratio (GER) in secondary education, measures total student enrollment regardless of age relative to the official school-age population (Barro & Lee, 2013). In macro-econometric modeling, secondary enrollment serves as a critical indicator of human capital accumulation and shifting environmental consciousness (Ahmed et al., 2020). Higher educational thresholds systematically enhance a society's capacity to adopt complex clean technologies, improve energy efficiency, and intensify public demand for robust environmental governance, thereby facilitating long-term carbon abatement (Lan et al., 2011).

3.2. Model specification and empirical strategy

To rigorously deconstruct the multi-dimensional nexus between disaggregated renewable energy consumption and environmental sustainability, this study adopts a sequential second-generation econometric strategy. Traditional first-generation estimators (such as basic ARDL or FMOLS) are highly susceptible to omitted variable bias and spurious inferences when applied to integrated global economies. Therefore, we explicitly deploy the Cross-Sectionally Augmented ARDL (CS-ARDL) framework. This advanced estimator is specifically chosen because it effectively neutralizes potential endogeneity - particularly the suspected two-way relationships among economic growth, financial development, energy utilization, and CO2 emissions. It achieves this by incorporating lagged dependent and independent variables, alongside cross-sectional averages that efficiently filter out unobserved global shocks, structural slope heterogeneity, and pervasive cross-sectional dependence (CSD).The empirical procedure progresses systematically: it begins with CSD and slope homogeneity diagnostics to validate the need for advanced estimators, followed by robust second-generation panel unit root testing (CADF and CIPS) to determine the integration order. Subsequently, the Westerlund (2007) error-correction-based test is applied to establish stable, long-run cointegrating equilibria. Ultimately, the long-run and short-run CS-ARDL estimations are complemented by the Dumitrescu & Hurlin (2012) heterogeneous panel causality test. This final step is crucial to move beyond static correlations, explicitly mapping the exact bidirectional causal directions and feedback loops among the variables to ensure a comprehensive treatment of the endogeneity issue.

3.3. Cross-sectional dependence test

Cross-sectional dependence (CSD) is pervasive in macro-panel data due to global spillovers and unobserved common shocks (Chudik et al., 2013). Left unaddressed, CSD severely biases traditional first-generation econometric estimators by violating their strict assumption of cross-sectional independence. To verify the presence of these interdependencies and justify the transition to robust second-generation techniques, we deploy the following diagnostic tests:

- CD test (Pesaran, 2004) for detecting strong cross-sectional dependence:

$$CD = \sqrt{\frac{2}{N(N-1)}} \sum_{i=0}^{N} \sum_{j=i+1}^{N} T_{ij} \hat{p}_{ij}^2 \rightarrow N(0,1) \quad (6)$$

Where ($\hat{p}_{ij}^2$) is the residual correlation coefficient between countries i and j, N is the number of countries, and T is the number of time periods. If the test rejects the null hypothesis of no cross-sectional dependence, it suggests that the countries under study are linked by common factors.

- the Pesaran (2015) CD test is additionally applied to detect mild or weak cross-sectional dependence within large-dimensional panels.

3.4. Slope homogeneity test

To evaluate whether slope coefficients are heterogeneous across cross-sectional units in large macro-panels, we apply the robust standardized homogeneity test introduced by Pesaran and Yamagata (2008), which is formulated as follows:

$$\tilde{\Delta} = \sqrt{N} \left(\frac{N^{-1} \tilde{S} - k}{\sqrt{2k}} \right) \quad (7)$$

where k is the number of regressors in the model, The properties of the small sample for testing $\tilde{\Delta}$ under normally distributed errors can be improved using the modified bias-corrected version, $\tilde{S}$ is the Swamy test statistic,

The small-sample properties of the test $\tilde{\Delta}$ under normally distributed errors can be improved using the following bias-adjusted version:

$$\tilde{\Delta}_{adj} = \sqrt{N} \left(\frac{N^{-1} \tilde{S} - E(\tilde{z}_{it})}{\sqrt{var(\tilde{z}_{it})}} \right) \quad (8)$$

Where $\mathrm{E}(\tilde{\mathrm{z}}_{\mathrm{it}})$ mathematical expectation of the statistic $(\tilde{\mathrm{z}}_{\mathrm{it}})$

3.5. Panel unit root test

To prevent the spurious inferences typically generated by first-generation estimators under cross-sectional dependence , we implement the second-generation Cross-Sectionally Augmented Dickey-Fuller (CADF) and IPS (CIPS) panel unit root tests (Pesaran, 2007). These frameworks ensure robust estimations under conditions of both pervasive CSD and structural slope heterogeneity, formulated as follows:

$$CADF_i = t_i(N,T) = (y_i^T \bar{M} y_{i-1})^{-1} (y_{i-1}^T \bar{M} \triangle y_i) \Big/ \sqrt{\sigma_i^2 (y_i^T \bar{M} y_{i-1})^{-1}} \quad (9)$$

where N is the number of cross-sectional units in the panel (e.g., countries or firms), and T is number of time periods per unit; these are the canonical panel dimensions in unit-root testing.

y_i^T: Value of the variable under study for unit i at time t ; $\Delta y_i^T = y_i^T - y_{i-1}^T$ denotes the first difference used in unit-root regressions.

Pesaran developed the cross-sectionally augmented IPS (CIPS) test using CADF as follows:

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} CADF_i \tag{10}$$

3.6. Panel cointegration test

To establish long-run cointegrating relationships while controlling for cross-sectional interdependencies, we apply the error-correction-based second-generation test by Westerlund (2007). This framework evaluates the null hypothesis of no cointegration by testing the significance of the speed-of-adjustment parameter, formulated as follows:

$$\Delta Y_{i,t} = \delta'_i d_t + \epsilon_i \left(Y_{i,t-1}\beta'_i X_{i,t-1}\right) + \sum_{j=1}^{p} \varphi_{i,j} Y_{i,j-1} + \sum_{j=0}^{p} \varphi_{i,j} Y_{i,j-1} + \mu_{i,t} \tag{11}$$

where ϵ_i represents the error-correction coefficient measuring the speed of adjustment toward equilibrium. Based on this, Westerlund computes four panel and mean group test statistics as follows:

$$G_t = \frac{1}{N}\sum_{i=i}^{N} \frac{\epsilon_i}{Se(\hat{\epsilon}_i)} \tag{12}$$

$$G_a = \frac{1}{N}\sum_{i=i}^{N} \frac{T\epsilon_i}{\epsilon_i(1)} \tag{13}$$

$$P_t = \frac{\hat{\epsilon}_i}{NSe(\hat{\epsilon}_i)} \tag{14}$$

$$P_a = T\ \hat{\epsilon}_i \tag{15}$$

The mean-group statistics Gt and Ga test for cointegration in at least one cross-sectional unit, while the panel statistics Pt and Pa evaluate cointegration across the entire panel. To ensure robust inferences under cross-sectional dependence, we rely on bootstrapped p-values

3.7. Cross-Sectionally Augmented ARDL (CS-ARDL)

To estimate the short- and long-run dynamics, this study employs the Cross-Sectionally Augmented ARDL (CS-ARDL) Mean Group estimator (Chudik & Pesaran, 2015). This framework is specifically selected for its capacity to accommodate mixed orders of integration and to filter out unobserved global shocks by augmenting unit-specific equations with cross-sectional averages. Crucially - and to explicitly address potential endogeneity and reverse causality between environmental quality, energy use, and macroeconomic drivers, the inclusion of lagged dependent and independent variables alongside lagged cross-sectional averages effectively neutralizes dynamic panel biases (Chudik et al., 2017). Consequently, the baseline CS-ARDL empirical specification is formulated as follows:

$$y_{it} = a_i + \sum_{l=1}^{Py} \lambda_{l,i}\, y_{i,t-l} + \sum_{l=0}^{P_x} \beta_{l,i} \chi_{i,t-l} \sum_{l=0}^{P_\varphi} \acute{\varphi}_{i,l} \bar{Z}_{i,t-l} + \varepsilon_{it} \tag{16}$$

The long-run coefficient for the Mean Group (MG) estimator is expressed as:

$$\hat{\theta}MG = {}^{1}/_{N} \sum_{i=1}^{N} \hat{\theta}_i \tag{17}$$

where $\hat{\theta}_i$ represents the individual long-run estimates for each cross-sectional unit. Additionally, the error correction representation of the CS-ARDL model is specified as follows:

$$\Delta y_{it} = \emptyset_i\left[y_{i,t-l} - \hat{\theta}_i x_{i,t}\right] - a_i + \sum_{l=1}^{P_{y-1}} \lambda_{l,i}\, \Delta_l y_{i,t-l} + \sum_{l=0}^{P_x} \beta_{l,i}\, \Delta_l x_{i,t-l} \sum_{l=0}^{P_\varphi} \acute{\varphi}_{i,l} \Delta_l \bar{Z}_{i,t-l} + \mathcal{u}_{it} \quad (18)$$

where $\emptyset_i$denotes the error correction speed of adjustment coefficient.

3.8. Heterogeneous Panel Causality Test

To determine directional causal linkages while strictly accounting for cross-sectional dependence and parameter heterogeneity, we employ the Dumitrescu and Hurlin (2012) heterogeneous panel causality test. By allowing causal dynamics to vary across individual cross-sectional units, this approach overcomes the restrictive homogeneity assumptions of standard Granger causality frameworks (Aouini et al., 2024). The test is specified as follows:

$$z_{i,t} = a_i + \sum_{j=1}^{p} \beta_i^j\, z_{i,t-j} + \sum_{j=1}^{p} \gamma_i^j\, T_{i,t-j} \quad (19)$$

In this panel model, $z_{i,t}$ represents the dependent variable, while α_i denotes unit-specific fixed effects, and p is the maximum lag order. The parameters β_i^j and γ_i^j represent the slope coefficients for the lagged dependent variable $z_{i,t-j}$ and the lagged independent variable $T_{i,t-j}$, respectively. Crucially, the subscript i on these coefficients econometrically captures structural slope heterogeneity across cross-sectional units.

4. Empirical results

This section delivers a rigorous empirical assessment of the intricate nexus between disaggregated renewable energy consumption, macroeconomic dynamics, and environmental sustainability. Utilizing a panel dataset of 29 countries spanning the period from 1990 to 2023, we systematically scrutinize both the long-run cointegrating equilibria and the underlying directional causal pathways among the core variables. Specifically, the analytical framework models environmental quality (proxied by CO2 emissions) against disaggregated renewable energy components encompassing solar, wind, hydro, and biofuel consumption alongside a comprehensive suite of macroeconomic covariates, namely economic growth (GDP), trade openness, globalization, financial development, human development, and renewable energy R&D expenditures.

4.1. Descriptive statistics

Table 2 presents the descriptive statistics for the main variables used in the study, including the number of observations (Obs), the arithmetic mean (Mean), the standard deviation (Std. dev.), the minimum (Min), and the maximum (Max) for each variable. These figures provide a comprehensive overview of the data's characteristics and distribution over the study period.

Table 2 - Descriptive statistics results

Variable	Obs	Mean	Std. dev.	Min	Max
CO2	928	665392.2	1515352	27330	1.07e+07
Solar	928	12.06707	55.08063	0	855.653
Wind	928	34.73514	122.4578	0	1715.493
Hydro	928	217.4863	424.6175	0	3471.19
Biofuel	928	21.62358	60.03914	0	415.87
TOT_REN	928	309.057	610.2253	0.271	6545.095
FIN	928	96.41274	50.031	3.956824	217.7609
HDI	928	0.8242112	0.1121174	0.434	0.962
RDERET	928	3348.8	2001.648	72.46093	7930.181

The descriptive statistics for the balanced panel dataset reveals substantial cross-country asymmetries. CO2 emissions exhibit extreme dispersion (Mean: 665,392.2; SD: 1,515,352), highlighting vast differences in economic scale. Within the renewable energy mix, hydropower dominates (Mean: 217.49), followed by wind (34.74), biofuels (21.62), and solar (12.07), where zero minimums mark early-stage technology adoption. Macroeconomic covariates also reflect deep structural gaps: financial development (FIN) and HDI span wide intervals (3.96–217.76 and 0.434–0.962, respectively), while green R&D (RDERET) averages 3,348.8 with high volatility (SD: 2,001.65). These pronounced variations and parameter heterogeneities robustly justify using second-generation econometric frameworks, such as CS-ARDL, to capture cross-sectional dynamics accurately.

4.2. Cross-sectional dependence analysis

Before proceeding with unit root and cointegration estimations, it is methodologically essential to test for cross-sectional dependence to ensure proper econometric model selection. Table 3 presents the diagnostic results from five complementary testing frameworks applied across all studied variables: the Lagrange Multiplier (LM) test, the Scaled LM test, the Pesaran (2004) CD test, the Bias-corrected scaled LM test, and the Pesaran (2015) CD test for weak cross-sectional dependence.

Table 3- Cross-sectional dependence results

Variables	Lagrange Multiplier LM test		Scaled LM test		Pesaran (2004) CD test		Bias-corrected scaled LM test		Pesaran (2015) CD test for weak cross-sectional dependence	
	CD	P-Value	Statistic	P-Value	Statistic	P-Value	CD	P-Value	CD	P-Value
CO_2	5199.38	0.000	168.214	0.000	19.64	0.000	167.71	0.000	24.530	0.000
SOLAR	6775.86	0.000	223.538	0.000	80.14	0.000	223.07	0.000	14.371	0.000
WIND	7717.24	0.000	278.021	0.000	86.41	0.000	277.58	0.000	40.659	0.000
HYDRO	1431.99	0.000	38.3334	0.000	5.60	0.000	37.881	0.000	54.350	0.000
BIOFUEL	2067.30	0.000	96.303	0.000	41.86	0.000	95.981	0.000	43.047	0.000
TOT_REN	8439.24	0.000	281.911	0.000	89.01	0.000	281.44	0.000	83.455	0.000
GDP	11022.7	0.000	372.575	0.000	104.94	0.000	372.05	0.000	100.241	0.000
FIN	1570.11	0.000	48.8375	0.000	21.14	0.000	48.025	0.000	36.110	0.000
HDI	12063.6	0.000	409.103	0.000	109.55	0.000	408.63	0.000	85.199	0.000
RDERET	3038.35	0.000	92.37751	0.000	37.00	0.000	91.773	0.000	31.064	0.000

The diagnostic outcomes reveal a stark, unanimous verdict across all five econometric frameworks, as every investigated indicator yields test statistics that are highly significant at the one percent threshold, with p-values consistently at zero. This sweeping rejection of the null hypothesis delivers definitive proof that the sampled nations are bound by dense, systemic spillover networks where localized structural or policy shocks do not occur in isolation but propagate dynamically across borders. Such pervasive cross-sectional dependence highlights the severe vulnerability of traditional panel techniques to size distortions, thereby firmly validating the transition to cross-sectionally robust, second-generation estimators for the subsequent analysis.

4.3. Homogeneity analysis

Table 4 delineates the slope homogeneity test results, focusing on the Delta and adjusted Delta statistics. These diagnostics formally evaluate the null hypothesis of parameter uniformity to detect structural slope heterogeneity across the cross-sectional units. By establishing statistical significance, these findings serve as a critical methodological guide, dictating the selection of appropriate, non-biased panel estimation strategies in the subsequent empirical analysis.

Table 4 - Heterogeneity test results

Empirical Model Specification	Delta Statistic (Δ)	P-Value	Adjusted Delta (Δadj)	P-Value
Model 1: Impact of Solar Energy on CO_2 Emissions	5.823	0.000	7.911	0.000
Model 2: Impact of Wind Energy onCO_2 Emissions	12.844	0.000	16.564	0.000
Model 3: Impact of Hydropower on CO_2 Emissions	9.715	0.000	12.475	0.000
Model 4: Impact of Biofuel on CO_2 Emissions	9.493	0.000	13.265	0.000
Model 5: Impact of Total Renewable Energy on CO_2 Emissions	11.281	0.000	14.439	0.000

The table above reports the slope homogeneity test results, where both statistics lead to a decisive rejection of the null hypothesis of parameter uniformity at the 1% significance level. This confirms

the presence of structural slope heterogeneity across the sampled countries. Consequently, these findings mandate the application of second-generation panel data econometrics that can effectively accommodate both cross-sectional dependence and parameter asymmetry.

4.4. Stationarity analysis

Table 5 delineates the empirical findings from the second-generation panel unit root tests, implementing the CADF and CIPS testing procedures at both levels and first differences. These diagnostics evaluate the stationarity properties and establish the precise order of integration for each series, thereby providing the necessary econometric justification for subsequent cointegration analyses and model specifications. Standard statistical significance levels are denoted by asterisks.

Table 5 - Stationarity analysis results

Variables	CIPS				CADF			
	Levels		1ST Difference		Levels		1ST Difference	
	Constant	Constant & Trend	Constant	Constant & Trend	Constant	Constant & Trend	Constant	Constant & Trend
CO_2	-1.705	-2.754**	-4.774***	-4.867***	-1.459	-2.607**	-3.733***	-3.714***
SOLAR	-0.807	-1.527	-3.076***	-3.776***	-1.273	-1.811	-2.584***	-3.212***
WIND	-2.075	-2.432	-4.356***	-4.594***	-2.363***	-2.724**	-3.540***	-3.576***
HYDRO	-3.417***	-4.187***	-5.904***	-6.134***	-2.655***	-3.462***	-5.073***	-5.174***
BIOFUEL	-2.142	-2.317	-4.105***	-4.130***	-2.646***	-2.471	-3.112***	-3.163***
TOT_REN	-2.696***	-3.041***	-5.554***	-5.712***	-2.315***	-2.668**	-4.093***	-4.133***
GDP	-2.060	-2.044	-3.561***	-3.632***	-2.015*	-2.039	-2.718***	-2.768***
FIN	-1.598	-1.863	-3.526***	-3.792***	-1.793	-2.026	-2.779***	-3.056***
HDI	-2.180**	-2.076	4.641***	-4.810***	-2.102**	-2.186	-3.262***	-3.502***
RDERET	-1.427	-1.288	-3.205***	-3.728***	-1.519	-1.433	-2.067***	-2.653***

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

Table 5 presents the empirical results of the second-generation panel unit root tests. According to the Cross-Sectionally Augmented IPS (CIPS) evaluation, hydropower and total renewable energy consumption are stationary at levels, denoted as $I(0)$, whereas the remaining variables carbon dioxide emissions, solar energy, wind energy, biofuel consumption, economic growth, financial development, the Human Development Index, and renewable energy R&D expenditures become stationary only after taking their first differences, denoted as $I(1)$. In contrast, the Cross-Sectionally Augmented Dickey-Fuller (CADF) test indicates that hydropower, total renewable energy, and wind energy are integrated of order zero $I(0)$, while the rest of the covariates stabilize at their first differences. Collectively, these diagnostics decisively reject the null hypothesis of a unit root, establishing a mixed order of integration among the series with a primary convergence to stationarity at the first difference.

4.5. Second-Generation panel cointegration test

The table 6 presents the results of the Westerlund (2007) panel cointegration test, reporting the Gt, Ga, Pt, and Pa statistics alongside their Z-values, conventional p-values, and robust p-values. These diagnostics evaluate the existence of a long-term cointegrating relationship among the variables under cross-sectional dependence, thereby guiding the selection of suitable second-generation panel estimators for subsequent analysis

Table 6 - Second-Generation Panel Cointegration Test Results

Estimated Model (Added Independent Variable)	Gt Statistic	Ga Statistic	Pt Statistic	Pa Statistic
Model 1: Solar Energy	-2.964***	-10.724***	-15.668***	-11.296***
	(4.053)	(0.701)	(4.530)	(2.210)
Model 2: Wind Energy	-2.937***	-10.341***	-12.248**	-7.204
	(3.771)	(0.936)	(2.023)	(0.541)
Model 3: Hydropower	-3.479***	-11.658*	-19.451***	-12.484**
	(-2.670)	(4.365)	(-4.730)	(1.875)
Model 4: Biofuel	-2.715***	-9.685**	-10.596*	-8.874**
	(-2.272)	(1.188)	(-1.785)	(-0.474)
Model 5: Total Renewable Energy	-2.818***	-10.791***	-12.470*	-8.016*
	(-3.277)	(0.654)	(-1.913)	(0.011)

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

The consolidated empirical results of the Westerlund (2007) cointegration test deliver a decisive and uniform rejection of the null hypothesis of no cointegration across all five estimated specifications. Relying on robust bootstrap-generated p-values that control cross-sectional dependence and slope heterogeneity, the test statistics particularly G_t and P_t exhibit strong statistical significance at conventional thresholds (1%, 5%, and 10%). This empirical consensus provides robust economic evidence of a stable, long-run cointegrating equilibrium binding carbon dioxide emissions to both the disaggregated and aggregate renewable energy components alongside the macroeconomic covariates. Ultimately, establishing this long-run relationship validates the structural integrity of the models, justifying the transition to second-generation dynamic estimators, such as the CS-ARDL framework, to capture efficient and unbiased long-run and short-run elasticity coefficients.

4.6. The Cross-Sectionally Augmented ARDL (CS-ARDL) Model

Following the confirmation of cross-sectional dependence, stationarity properties, and long-run cointegration, the econometric analysis evaluates the dynamic impact of renewable energy on emissions. Given that panel diagnostics reveal severe cross-sectional dependence and slope heterogeneity, traditional first-generation estimators are rendered invalid. Consequently, this study employs the advanced second-generation Cross-Sectionally Augmented ARDL (CS-ARDL) framework, which filters out global shocks and endogeneity via cross-sectional averages. To complement these long-run estimations and uncover true directional feedback loops beyond static

correlations, the analysis incorporates the heterogeneous panel causality test by Dumitrescu & Hurlin (2012), with all causal decision pathways detailed in Table 7.

Table 7 - Cross-Sectionally Augmented ARDL (CS-ARDL) results

Structural variables	Model 1 (SOLAR)	Model 2 (WIND)	Model 3 (HYDRO)	Model 4 (BIOFUEL)	Model 5 (TOT_REN)
	Short Run (SR)				
Δ Energy Var.	-0.0185* (0.0103)	-0.0498** (0.0200)	-0.0670** (0.0296)	-0.0779* (0.0408)	-0.1025** (0.0407)
Δ GDP	0.4451** (0.1797)	0.9436*** (0.1925)	0.6427*** (0.1922)	1.2802*** (0.4744)	1.5077*** (0.3716)
Δ FIN	0.0746 (0.0793)	-0.0300 (0.0829)	0.0562 (0.0732)	0.1122 (0.2201)	0.1433* (0.0803)
Δ HDI	0.2010 (1.1043)	-0.5956 (0.8595)	-3.4781*** (1.1103)	-0.1845 (1.8167)	-3.2597* (1.8311)
Δ RDERET	-0.2546* (0.1348)	-0.0764 (0.0916)	-0.4216*** (1.1099)	0.4638 (0.2847)	-0.2837*** (1.1098)
	Long Run (LR)				
ECT_{t-1}	-0.8931*** (0.0507)	-0.5495*** (0.0374)	-0.9161*** (0.0576)	-0.5775*** (0.0467)	-0.9437*** (0.0719)
Energy Var.	-0.0230* (0.0130)	-0.0852*** (0.0322)	-0.0741* (0.0386)	-0.1586** (0.0741)	-0.2065* (0.1085)
GDP	0.6686** (0.2795)	1.9440*** (0.5060)	1.0686** (0.4958)	2.3198*** (0.8875)	2.0659*** (0.6917)
FIN	0.1326 (1.1052)	-0.1983 (0.2031)	0.0745 (0.0810)	0.3761 (0.4714)	0.1366* (0.0791)
HDI	1.1214 (1.5212)	-2.1767 (2.5480)	-3.6824*** (1.3148)	-0.1563 (2.8785)	-1.5023 (2.0626)
RDERET	-0.3015* (0.1595)	-0.0153 (0.1850)	-0.4783*** (0.1259)	0.7368 (0.6042)	-0.4495** (0.2084)
	Diagnostics				
Pesaran CD (Stat)	4.74	2.07	4.77	1.72	3.45

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

The condensed estimation outputs of the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model reveal robust econometric consistency across the estimated horizons.

In the short run, all renewable energy sources (both disaggregated and aggregate) exert a negative and statistically significant impact on curbing carbon dioxide emissions. This mitigating effect is

led by total renewable energy consumption, which records the highest short-run elasticity (-0.1025), and is further bolstered by the environmentally protective role of green research and development expenditures. Conversely, economic growth exerts a critically significant positive impact, acting as a direct driver of increased short-run pollution.

In the long run, the negative and strictly significant error correction term establishes a highly stable dynamic adjustment mechanism. This guarantees a rapid convergence back to the cointegrating equilibrium path within the first year following an external shock, with adjustment speeds ranging from 54.95% to 94.37%. This long-run steady state is characterized by a sustained, significant emission-reducing influence from renewable energies peaking at an elasticity of -0.2065 for the aggregate index. This protective effect is strongly reinforced by the carbon-mitigating roles of research and development expenditures and the Human Development Index (particularly within the hydropower specification). Meanwhile, economic growth persists as the primary structural driver of emissions, while financial development maintains general statistical neutrality across both time horizons.

Regarding diagnostic testing, the post-estimation results from the Pesaran CD test confirm the framework's methodological validity. Across all five models, the computed CD statistics are statistically insignificant (with p-values well exceeding the 10% threshold). This successfully demonstrates that the CS-ARDL approach has effectively addressed and eliminated cross-sectional dependence from the error terms, thereby ensuring that the estimated parameters are efficient, unbiased, and highly dependable for policy formulation.

4.7. Dumitrescu & Hurlin (2012) heterogeneous panel causality test

Following the estimation of the long- and short-run dynamic relationships using the CS-ARDL framework, the next essential econometric step is to determine the directional causality between the study variables and carbon dioxide CO_2 emissions. Given that conventional causality tests assume cross-sectional homogeneity, this study implements the second-generation heterogeneous panel causality test developed by Dumitrescu and Hurlin (2012). This advanced methodology effectively identifies whether the causal dynamics are unidirectional or bidirectional while strictly accounting for cross-sectional dependence and slope heterogeneity across the sampled nations. The empirical findings are summarized in Table 8.

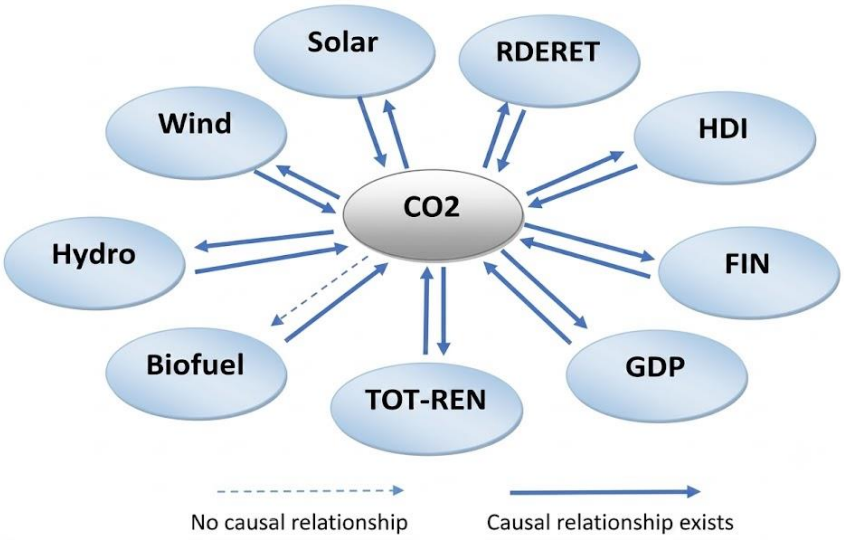
Table 8 - Results of Dumitrescu & Hurlin (2012) heterogeneous panel causality test

Null Hypothesis	WALL-Stat	Zbar-Stat	P-value	Decision
SOLAR ≠ > CO_2	5.2744	16.2765	0.000	SOLAR ⇔ CO2
CO_2 ≠ > SOLAR	3.6498	10.0903	0.000	
WIND ≠ > CO_2	3.7388	7.9848	0.000	WIND ⇔ CO2
CO_2≠ > WIND	4.3968	9.9033	0.000	
HYDRO ≠ > CO_2	2.5253	4.4470	0.000	HYDRO ⇔ CO2
CO_2≠ > HYDRO	2.7279	5.0377	0.000	
BIOFUEL ≠ > CO_2	3.0850	5.9636	0.000	BIOFUEL ⇒CO2
CO_2≠ > BIOFUEL	0.9980	-0.234	0.715	
TOT_REN ≠ > CO_2	4.5746	13.6118	0.000	TOT_REN ⇔ CO2
CO_2≠ > TOT_REN	2.5046	5.7295	0.000	

GDP ≠ > CO_2	2.7279	4.2499	0.000	GDP ⇔ CO2
CO_2≠ > GDP	2.0036	3.8216	0.000	
FIN ≠ > CO_2	3.8520	10.8599	0.000	FIN ⇔ CO2
CO_2≠ > FIN	4.0715	11.6961	0.000	
HDI ≠ > CO_2	3.2448	8.5480	0.000	HDI ⇔ CO2
CO_2≠ > HDI	1.6394	2.4346	0.014	
RDERET ≠ > CO_2	3.3146	8.8137	0.000	RDERET ⇔ CO2
CO_2≠ > RDERET	4.1582	12.0259	0.000	

The empirical findings of the Dumitrescu and Hurlin (2012) causality test reveal two structural pathways: the first is a unidirectional causal relationship running exclusively from biofuel energy to carbon dioxide CO_2 emissions, confirming that biomass consumption acts as a direct determinant of environmental degradation without a feedback effect. The second pathway entails a bidirectional causal relationship (feedback mechanism) linking CO_2 emissions with all remaining variables, including the other energy sources (solar, wind, hydropower, and total renewable energy) and macroeconomic indicators (economic growth, financial development, human development, and research and development expenditures). This demonstrates the intrinsic interconnectivity and dynamic interdependence between the environmental system and the developmental and technological sectors across the sampled nations.

Figure 1 - The Causal Relationship Between CO_2 Emissions and study Variables



The preceding figure demonstrates that promoting renewable energy sources can play a pivotal role in mitigating and controlling carbon dioxide CO_2 emissions, highlighting the critical importance of strategic policymaking to balance economic growth with environmental sustainability. Moreover, for policymakers, these empirical findings provide robust evidence of the imperative to support and subsidize research and development (R&D) in green technologies. Such innovations not only directly aid in reducing CO_2emissions but are also dynamically influenced by emission thresholds, thereby establishing a continuous feedback loop.

5. Economic interpretations of the results

This study moves beyond an isolated statistical evaluation of clean energy's impact by constructing an overarching narrative centered on the matrix of energy transition and macroeconomic-environmental equilibrium. The econometric outputs for our 29-nation sample, spanning the historical period from 1990 to 2023, reveal a complex system where policies do not operate in a vacuum. Instead, disaggregated renewable energy sources and macro-structural indicators intertwine to forge a stable dynamic equilibrium governed by reciprocal causal relationships and continuous feedback loops. This methodological diversity in selecting a sample that deliberately balances OECD giants with major emerging markets explains the stark structural variations in environmental emissions and the scale of eco-innovation across nations. Consequently, these findings highlight a compelling economic and structural reality: the capacity of institutionally and technologically advanced economies to reap the benefits of clean energy differs fundamentally from that of emerging nations still grappling with the early stages of adopting and localizing these technologies.

Translating the elasticities of the Cross-Sectionally Augmented ARDL (CS-ARDL) model into tangible reality yields a robust validation of the environmental energy substitution hypothesis. Methodologically, prior to interpreting these outcomes, the model was rigorously tested for potential structural breaks. To further evaluate the temporal stability of the estimated coefficients and guarantee overall model consistency, we performed an exhaustive residual analysis and diagnostic checking. The Pesaran CD test statistic recorded a value of 3.45 with a corresponding p-value of 0.8127. Since this p-value considerably exceeds the 0.05 significance threshold, we fail to reject the null hypothesis of cross-sectional independence, confirming the complete absence of residual cross-sectional dependence. This demonstrates that the underlying relationship between the explanatory variables and CO2 emissions exhibits high structural stability, proving the model is entirely free from unaddressed structural breaks that could otherwise compromise the credibility of the long-run empirical estimates.

Consequent to this rigorous validation, in the short run, all renewable energy sources exert a significant mitigating impact on carbon emissions. This mitigating effect is led by total renewable energy consumption, which records a short-run elasticity of -0.1025. Economically, this coefficient implies that a 1% increase in clean energy utilization instantly curbs carbon dioxide emissions by 0.1025%. This reveals that the initial integration of clean energy into national grids yields immediate environmental dividends by displacing marginal, carbon-intensive fossil fuel combustion. In the long run, this environmental efficiency structurally amplifies, as evidenced by the aggregate long-run elasticity coefficient of -0.2065. Economically, this doubling of efficiency signifies that a 1% permanent expansion in clean energy portfolios contracts long-run carbon emissions by 0.2065%. This phenomenon clearly embodies the attainment of economies of scale and technological learning curves; as green infrastructure matures and investments stabilize, production costs plummet, and clean energy vectors successfully achieve widespread structural substitution over legacy fossil fuels. Looking at the disaggregated vectors, wind energy and biofuel consumption emerge as highly potent drivers in the long run, exhibiting protective elasticities of -0.0852 and -0.1586 respectively, which demonstrates that technology-specific clean energy profiles dictate the trajectory of carbon mitigation unevenly across temporal horizons.

Yet, despite this protective role of clean energy, the green transition collides with a formidable positive impact and an alarming surge in the elasticity of economic growth. Real gross domestic product growth persists as the primary structural driver of pollution across all specifications, with short-run elasticities ranging from 0.4451 to 1.5077 and expanding dramatically in the long run to reach a peak elasticity of 2.3198 in the biofuel specification. Economically, this coefficient means

that a 1% acceleration in economic output generates a staggering 2.32% surge in carbon emissions. This massive expansion reflects the absolute dominance of the scale effect, proving that the engines of production and industrial expansion across these nations remain fundamentally carbon intensive. Theoretically, this consensus provides robust empirical proof that the sampled nations collectively occupy the upward-sloping segment of the Environmental Kuznets Curve (EKC), having yet to reach the critical turning point where absolute decoupling between material prosperity and environmental degradation materializes.

The profound diagnostic value of this analysis lies in penetrating the depth of variables that appeared statistically neutral or exceptional to interpret their behavior from a concrete structural standpoint. In this regard, the general statistical neutrality of the financial development variable across both short- and long-run horizons serves as a warning call of market failure to policymakers. This neutrality reveals a deep credit misallocation gap within the private banking sectors; commercial banks distribute credit based on purely commercial profitability and conventional solvency without anchoring it to Environmental, Social, and Governance (ESG) criteria. This environmental blindness deprives clean initiatives of preferential financing, leaving green infrastructure to contend with prohibitive upfront investment costs while carbon-heavy conventional industries enjoy continuous credit expansion. Conversely, biofuel consumption constitutes a striking structural exception. The causality test uncovers an exclusive unidirectional causal relationship running straight from biofuel consumption to carbon dioxide emissions without any feedback effect, whereas all other energy vectors exhibit bidirectional feedback loops. The economic explanation for this unique rigidity lies in the non-negotiable, structural nature of biofuel-dependent sectors such as agriculture and conventional heavy transport. While variations in biofuel consumption directly dictate ambient pollution levels as an independent explanatory driver, the existing volume of atmospheric emissions does not act as an immediate regulatory or political catalyst to alter its utilization patterns, due to the acute lack of flexible technological alternatives in these vital baseline industries.

Furthermore, the error correction term in this framework provides a crucial economic reading that embodies the exceptional dynamic resilience of the macro-environmental system. Its strictly negative and highly significant coefficients at the 1% level - closely approaching unity at -0.9437 in the aggregate model - confirm that the macro-system complies with an ultra-fast self-correcting mechanism. Specifically, this value indicates that if an external economic or environmental shock disrupts the system, a remarkable 94.37% of the structural disequilibrium is automatically rectified and pulled back toward the long-run steady-state cointegrating path within the very first year following the shock.

To operationalize this sustainable self-resilience, governments must devise an intelligent temporal sequencing in formulating their macroeconomic policies. In the short run, immediate and direct financial support must be channeled toward eco-innovation research and development expenditures, as public green R&D serves as an instantaneous carbon-mitigating tool whose prompt efficacy in reducing short-run emissions is robustly validated by a significant protective coefficient of -0.4216 in the hydropower specification. In the long run, strategic support must pivot toward heavy investment in human capital, elevating the Human Development Index and secondary school enrollment rates. As demonstrated by the highly significant long-run coefficient of -3.6824 for the Human Development Index in the hydropower model, a minor upgrade in human well-being and education contracts carbon emissions by 3.6824%. Human capital represents the ultimate structural channel capable of transforming societal members from passive consumers into environmentally conscious citizens, while simultaneously developing the highly skilled workforce required to operate and manage advanced green energy grids as a sustainable, long-term alternative.

Finally, this analysis positions itself precisely within the discourse of contemporary scientific debate. In its advocacy for the protective role of clean energy and green innovation, it converges with rigorous literature that champions the Porter Hypothesis - the notion that well-designed environmental regulations stimulate efficiency and innovation rather than hindering economic competitiveness (Han et al., 2025; Feng, 2022; Udeagha & Ngepah, 2023). However, this analysis diverges from frameworks focused exclusively on advanced economies. The reason for this divergence stems from the comprehensive scope of the current sample, which encompasses massive emerging markets where growth priorities still compete with stringent environmental mandates. Given that these 29 nations drive the global economy and account for the lion's share of global energy demand, the model attains high external validity, making it highly valuable for formulating shared international policies. Nonetheless, the trap of structural heterogeneity - confirmed by our rigorous homogeneity tests showing significant Delta statistics at the 1% level - strictly prohibits the imposition of standardized or pre-packaged policy toolkits. Accordingly, true success in the green transition demands the formulation of flexible international agreements centered on facilitating technology transfer from advanced economies and providing concessional green financing packages that empower developing and emerging nations to clear the critical phase of the Kuznets curve without paying an irreversible ecological toll.

6. Conclusion

This study delivers a rigorous empirical assessment of the intricate nexus between disaggregated renewable energy consumption, macroeconomic dynamics, and environmental sustainability across a comprehensive sample of 29 nations spanning the period from 1990 to 2023. Employing advanced second-generation panel econometric methods specifically the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) framework and Westerlund cointegration diagnostics the analysis explicitly accounts for pervasive cross-sectional dependence and structural slope heterogeneity across the sampled economies.

The empirical evidence confirms that achieving carbon neutrality cannot rely on isolated policy interventions but requires a systemic, long-run equilibrium approach that binds carbon dioxide (CO2) emissions to both aggregate and disaggregated clean energy portfolios, economic expansion, financial structures, and human capabilities. By bridging advanced OECD members and major emerging markets, the study captures profound cross-country asymmetries and macroeconomic variances, moving the environmental degradation discourse beyond simplistic, one-size-fits-all generalities. The empirical findings demonstrate that all disaggregated renewable energy sources (solar, wind, hydro, and biofuel) alongside the aggregate index exert a statistically significant mitigating effect on CO2 emissions across both short- and long-run horizons, verifying the environmental energy substitution hypothesis as clean portfolios successfully displace polluting fossil fuels. Conversely, the analysis reveals a massive, robust positive impact of economic growth on emissions, where the long-run elasticity significantly amplifies across all specifications. This surge underscores the absolute dominance of the "scale effect," proving that industrial expansion across these 29 nations remains fundamentally carbon-intensive and tied to traditional fuel consumption.

Dynamic causality testing via the Dumitrescu and Hurlin framework further maps out these interactions, revealing pervasive bidirectional feedback loops among CO2 emissions, green R&D spending, human development, and most energy vectors, which indicates a mutually reinforcing system where progress in clean technology deployment actively responds to and accelerates environmental quality adjustments. The overwhelming scale effect driven by economic growth

theoretically positions the sampled nations collectively on the upward-sloping segment of the Environmental Kuznets Curve (EKC), indicating that absolute decoupling between material prosperity and ecological degradation has not yet materialized. Amidst these findings, the study uncovers critical structural anomalies and implementation gaps, most notably the general statistical neutrality of financial development across both temporal horizons. This neutrality exposes a vital institutional failure: banking credit allocation to the private sector remains "environmentally blind," prioritizing conventional commercial solvency over Environmental, Social, and Governance criteria, thereby depriving clean initiatives of preferential financing. Furthermore, biomass consumption stands as a unique structural exception, exhibiting an exclusive unidirectional causal pathway running straight to CO2 emissions without a feedback effect. This dynamic reflects the rigid, non-negotiable nature of biofuel-dependent sectors like agriculture and transport, which directly dictate pollution levels but fail to dynamically adjust their consumption patterns in response to ambient atmospheric emission thresholds.

For policymakers, the highly significant and near-unity error correction terms provide a reassuring indicator of macroeconomic resilience, demonstrating an ultra-fast self-correcting mechanism that rectifies 54% to 94% of structural disequilibria within the first year following an external shock. Capitalizing on this systemic flexibility demands strategic policy sequencing: in the short run, immediate financial subsidies must be channeled into green research and development expenditures, which demonstrate an instantaneous, statistically significant capacity to abate carbon emissions. In the long run, policy frameworks must pivot heavily toward human capital accumulation by upgrading secondary educational attainment and the Human Development Index. Cultivating a highly skilled, environmentally conscious labor force serves as the ultimate structural catalyst, transforming passive consumers into active advocates for stringent regulations while building the technical expertise required to manage and optimize advanced distributed green energy grids.

Ultimately, the study highlights that green growth can only emerge where energy diversification, innovation architecture, and human capabilities converge into an integrated policy mix. While the model enjoys high external validity due to the sample accounting for the lion's share of global GDP and aggregate energy demand, the presence of structural slope heterogeneity strictly cautions against importing rigid, uniform regulatory mandates. Instead, international climate frameworks must prioritize flexible bilateral agreements, streamlined green technology transfers, and concessional financing packages. This targeted support is essential to empower emerging and developing economies to safely clear the critical turning point of the Kuznets curve without paying a devastating and irreversible ecological toll.

7. Policy implications

The empirical findings of this study translate directly into a suite of targeted strategic guidelines, enabling decision-makers to forge a structural balance between economic expansion and environmental responsibility through coordinated temporal engineering. First, driven by the significant short-run mitigating impact of green R&D and its confirmed bidirectional causality with (CO_2) emissions, governments must inject immediate and targeted financial subsidies to support eco-innovation. This ensures that technological advancements remain dynamically responsive to existing pollution thresholds. Second, guided by the strong negative long-run elasticity of human capabilities, strategic investments must pivot toward elevating the Human Development Index and secondary education enrollment rates. Education serves as the ultimate structural channel to transform societal members from passive consumers into environmentally conscious citizens,

while qualifying the highly skilled workforce required to manage advanced distributed renewable grids. Third, responding directly to the alarming statistical neutrality of the financial development variable across all models, regulatory intervention is urgently required. Central banks must eliminate the state of "environmental blindness" in commercial credit allocation by mandating the strict integration of Environmental, Social, and Governance (ESG) criteria into private sector financing. Policymakers should introduce preferential credit incentives for green projects rather than burdening them with prohibitive commercial interest rates. Finally, dictated by the confirmed structural slope heterogeneity among the sampled nations, this study cautions against adopting pre-packaged, cross-border regulatory policies. Instead, true transitional success requires flexible international agreements that facilitate green technology transfer and provide concessional financing packages, empowering emerging economies to safely clear the critical segment of the Environmental Kuznets Curve without paying a catastrophic ecological toll.

8. Research limitations and future directions

While this study provides robust macroeconomic insights, several limitations must be explicitly acknowledged. First, the empirical scope evaluates environmental degradation exclusively through the lens of carbon dioxide (CO_2) emissions. Future research should expand the dependent variable to encompass a broader holistic metric, such as the Ecological Footprint Index or other greenhouse gases (e.g., Methane), to capture multi-dimensional environmental pressures. Second, while the 29-country balanced panel successfully bridges advanced OECD and major emerging markets, it inherently excludes least developed countries (LDCs) and highly fragile economies due to strict data continuity requirements. Consequently, the estimated elasticities and policy thresholds may not perfectly generalize to these excluded regions. Finally, the proxy utilized for financial development captures aggregate domestic credit to the private sector. Due to the unavailability of uninterrupted specific green finance datasets spanning the entire 1990–2023 timeline, the model cannot isolate the precise impact of targeted green bonds or environmental taxation. Future studies with access to highly disaggregated green finance data could further refine the nuances of the financial-environmental nexus.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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