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ORIGINAL PAPER
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INDUSTRIAL ACTIVITY, RENEWABLE ENERGY, AND INSTITUTIONAL FACTORS AS DRIVERS OF CO_2 EMISSIONS IN TEN HIGH-EMITTING ECONOMIES

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ABSTRACT

Motives: Carbon emissions in the world's major emitting economies remain high despite progress in renewable energy deployment and institutional reforms. Investigating how industrial activity, population growth, foreign investment, and governance shape emission trends is important for developing effective environmental policies.
Aim: This study investigates the determinants of carbon dioxide emissions in ten high-emitting economies from 1995 to 2023 using the Pooled Mean Group Autoregressive Distributed Lag (PMG-ARDL) and the Dynamic Common Correlated Effects estimator (DCCE), which capture both long-run equilibrium relationships and short-run dynamics while accounting for cross-country interdependence.
Results: Renewable energy consistently reduces emissions in both the short and long run. Manufacturing and research activity increase emissions, reflecting carbon-intensive industrial and innovation processes. Population growth reduces emissions in the long run, suggesting demographic-related efficiency gains. Foreign direct investment alone lowers emissions, but its interaction with regulatory quality raises emissions, showing that weak institutional frameworks can offset environmental progress. These findings support coordinated industrial, investment, and governance policies to achieve sustainable reductions in emissions in high-emitting economies.

Keywords: carbon emission, CO_2, industrialization, policy measures, renewable energy

INTRODUCTION

Carbon dioxide (CO_2) emissions are at the center of the global climate crisis, with far-reaching consequences for environmental stability, economic resilience, and public health. In 2020, the ten highest-emitting economies accounted for more than 60% of global CO_2 emissions (IEA, 2021). Their emission patterns and mitigation choices will strongly influence global efforts to limit climate risks. Understanding what drives emissions in these countries is essential for designing effective environmental strategies.

A wide range of structural and policy-related factors affect CO_2 emissions. Economic expansion often increases energy demand, typically met by fossil fuels, which raises emissions (Baba Ali

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et al., 2022; Sadorsky, 2014; Xu & Yang, 2019). The Environmental Kuznets Curve (EKC) suggests that emissions may initially rise with development but decline as economies adopt cleaner technologies and more efficient systems (Grossman & Krueger, 1995). Industrialization further adds pressure, as manufacturing and construction activities are highly energy-intensive, especially in rapidly transforming economies (Hasni et al., 2023; Ritchie et al., 2020). In many cases, industrial growth has outpaced environmental oversight and clean energy adoption, sustaining emission-intensive development.

Policy design and institutional arrangements shape emission trends. Regulatory measures, clean energy targets, and international cooperation can help limit emissions (IRENA, 2022), but their effectiveness depends on institutional capacity and long-term commitment (Ge & Zhang, 2023; Khan et al., 2023; Shen et al., 2020). Weak governance can reduce the impact of even well-designed policies.

This study investigates the determinants of CO_2 emissions in ten high-emitting economies from 1995 to 2023, focusing on the combined effects of industrial activity, population growth, foreign investment, and institutional quality. The study applies pooled mean group autoregressive distributed lag (PMG-ARDL) and the dynamic common correlated effect estimator (DCCE) to capture both long- and short-run relationships while accounting for cross-sectional dependence and unobserved common factors. By jointly investigating industrial activity, renewable energy use, and institutional policy quality, the study identifies which structural and governance factors are most closely associated with emission trends in the world's highest-emitting economies, thereby supporting the formulation of policies that promote cleaner industrial development and align national strategies with climate goals. The paper is structured as follows: Section 2 reviews relevant literature; Section 3 presents the methodology and data; Section 4 discusses the empirical results; and Section 5 concludes with policy implications.

LITERATURE REVIEW

Numerous studies have examined the drivers of carbon dioxide emissions, with growing attention to industrial development, renewable energy, and the role of policy and governance structures. Many of these studies apply panel data techniques to assess how emissions respond to structural and institutional factors across regions and income groups.

Ge and Zhang (2023) analyzed financial efficiency, environmental sustainability, and supply chain dynamics in BRICS economies. Their results show that while several sustainability indicators promote long-term growth, carbon emissions and foreign direct investment had limited effects on digital advancement. Similarly, Hoa et al. (2024) examined six developed countries and found that renewable energy, trade, and population growth significantly affect environmental quality, with fossil fuel use increasing emissions and renewable energy mitigating them.

Industrial activity remains a major determinant of emissions. Choudhury et al. (2023) employed a panel ARDL model to evaluate the effects of energy use and industrial output in high-emission countries, finding that while energy use strongly raises emissions, industrial output has a weaker long-run effect. Wang et al. (2023) reported that digital innovation reduces emissions in G7 countries, especially when combined with lower energy intensity and higher trade openness. Hassan (2023) further demonstrated that the effectiveness of energy-related tax policies in curbing emissions increases at higher emission levels.

Li et al. (2023) found that regulatory tools such as green taxation and environmental standards help reduce emissions in OECD economies. Shen et al. (2020) and Khan et al. (2023) emphasized that strong institutional frameworks and enforcement mechanisms are vital for environmental policy success. In many countries, weak governance limits the effectiveness of environmental regulations, even when policies appear well-designed.

Doğan et al. (2022) and Milindi and Inglesi-Lotz (2022) showed that eco-innovation and renewable

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energy adoption help lower emissions, especially in high-income economies, although rebound effects are observed in some emerging markets. Hwang (2023) analyzed Latin American countries and concluded that renewable energy expansion and digital transformation contribute jointly to emission reduction.

Jain and Kaur (2022) and Khan and Yahong (2022) found that income inequality worsens environmental degradation, while Przychodzen and Przychodzen (2020) linked renewable energy expansion to broader fiscal and labor conditions, including unemployment and public debt. Tawiah and Alessa (2024) observed that climate risk and vulnerability vary markedly between low- and high-emission countries, often constraining progress in lower-emitting regions. In the South Caucasus, Dilanchiev et al. (2024) discovered that emissions can influence renewable energy adoption, indicating feedback effects in energy transition efforts.

Samour et al. (2023) investigated the impact of the real estate market and renewable energy on ecological quality in Belgium using the ARDL bootstrap method. Their results show that real estate activity deteriorates environmental quality in both the short and long run. Similarly, Samour et al. (2022) examined the link between insurance market development and environmental quality in the UAE, confirming that renewable energy consumption improves environmental quality while a developed insurance market supports sustainability. Adeleye et al. (2021) analyzed the growth-energy-emissions nexus in seven South Asian countries and found that economic growth raises emissions, renewable energy lowers them, and non-renewable energy worsens environmental outcomes. Zhang et al. (2023) studied the United States and revealed that renewable energy transition, ecological innovation, and economic policy uncertainty reduce emissions, whereas globalization tends to increase them. Inuwa et al. (2025) examined India and concluded that natural resource rent and economic growth harm environmental quality, while renewable energy enhances sustainability.

Despite these contributions, gaps remain. Most existing studies analyze emissions across diverse income groups or regions but give limited attention to high-emitting economies, which account for the largest share of global emissions. In particular, the direct effects of industrial activity, such as manufacturing, energy-intensive production, and construction, are often treated in aggregate, without detailed sectoral consideration. The effectiveness of policy interventions in these situations has also not been systematically examined, especially where institutional challenges affect implementation.

Moreover, while many studies examine the impact of renewable energy adoption or regulation, they rarely assess how these interventions perform in economies where emissions are deeply tied to industrial structure. There is also a lack of cross-country panel studies that account for unobserved common factors and cross-sectional dependence, which can bias results in global comparative analyses.

This study addresses these shortcomings by focusing exclusively on the ten highest carbon-emitting economies from 1995 to 2023. It contributes to the literature in three ways. First, it provides a focused, up-to-date empirical investigation of emission drivers in countries that account for a majority of global CO_2 output. Second, it applies both the pooled mean group estimator and the dynamic common correlated effects model to account for both short- and long-run effects, while handling cross-sectional dependence and unobserved common shocks. Third, it integrates industrial structure and institutional quality variables in a unified panel framework, allowing for a clearer understanding of how emissions evolve in economies where policy enforcement and industrial intensity present unique challenges. The findings are expected to support more effective emission reduction strategies tailored to the realities of high-emitting economies.

Industrial emissions lock-in

The industrialization paths of high-emitting economies are deeply rooted in energy-intensive production structures that perpetuate long-term dependence on fossil fuels. Unlike some late-industrializing economies that have the potential to leapfrog into less car-

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bon-intensive sectors, countries such as China, India, the United States, and Russia have developed extensive manufacturing systems grounded in coal, oil, and natural gas (Ritchie et al., 2020; Unruh, 2000). These systems are not only technologically locked into fossil energy but also structurally embedded within global value chains that reward carbon-intensive exports such as steel, cement, and chemicals (Geels et al., 2017). As a result, economic growth and emissions remain tightly coupled-often despite significant policy reforms or technological improvements.

This persistent linkage is commonly described as "carbon lock-in", a condition reinforced by feedback mechanisms between infrastructure, industrial policy, and capital stock accumulation (Seto et al., 2016). Once high-emitting industrial systems are established, they generate long investment cycles and rigid supply chains, making rapid decarbonization economically and politically costly. Moreover, the political influence of fossil-dependent sectors frequently slows regulatory shifts, especially where energy security and employment are tied to heavy industry (Fouquet, 2016). Therefore, industrialization in high-emitting countries should not be viewed as a simple empirical driver of emissions, but as a structural constraint that actively impedes decarbonization.

Fig. 1 illustrates this structural constraint by tracing the directions of CO_2 emissions and manufacturing intensity across countries. Arrows show the evolution over time, and the shaded "lock-in zone" identifies cases where both emissions and manufacturing remain persistently high. Economies such as South Korea exhibit this lock-in pattern, reinforcing the theoretical claim that structural industrial dependence undermines mitigation progress. In contrast, countries like Germany or Japan demonstrate partial shifts toward lower-emission regimes but remain exposed to rebound effects and incomplete transitions. This emphasizes that emissions outcomes in high-carbon economies are often shaped more by entrenched industrial configurations than by policy ambition alone.

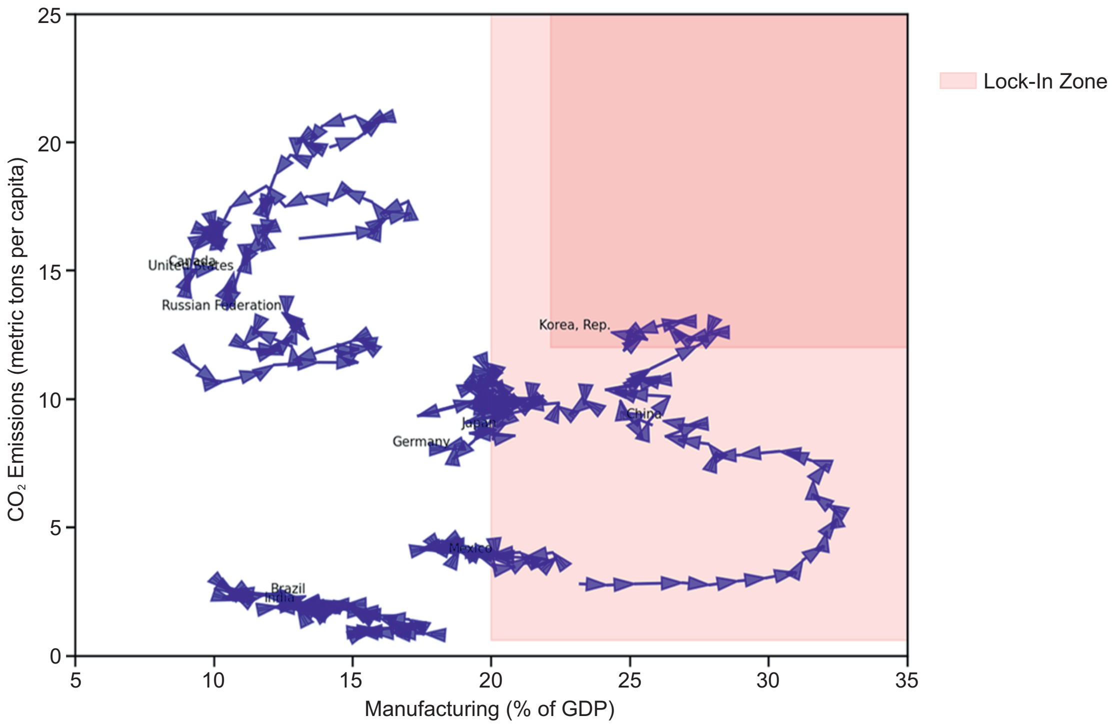

Fig. 1. Direction of industrial emissions lock-in
Source: Author's own plot based on World Bank data.

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Barriers to renewable energy uptake

Renewable energy has become a cornerstone of global decarbonization strategies, promoted for its potential to displace fossil fuel consumption and reduce carbon emissions. However, its effectiveness is highly uneven across national perspectives, especially in high-emitting economies. The diffusion of renewable technologies in these situations is often constrained by systemic and structural barriers, including the dominance of fossil-based infrastructure, legacy grid systems, and persistent fossil fuel subsidies (Sovacool, 2016). These constraints contribute to what York and Bell (2019) term the "renewables paradox", wherein renewable energy investment and capacity expansion occur alongside rising overall emissions. One underlying mechanism is the energy rebound effect. As new clean energy capacity is added or energy efficiency improves, total energy demand may rise due to expanded economic activity or behavioral responses, thus offsetting expected gains (Milindi & Inglesi-Lotz, 2022). In other cases, renewable energy simply adds to the existing energy mix rather than displacing coal or gas, especially where fossil fuel interests are entrenched or grid systems prioritize base-load fossil generation (Miketa & Merven, 2013). These dynamics are further complicated by the political economy of energy transitions, where fossil fuel incumbents engage in regulatory capture, soft resistance, or lobbying to delay renewable scale-up (Kuzemko et al., 2016). As a result, even in countries that report growing shares of renewable energy, carbon emissions may remain high or decline only marginally.

These dynamics help explain why the marginal effect of renewable energy on emissions is often weakened or statistically insignificant in upper emission quantiles, especially in carbon-intensive economies. The relationship is not purely technological

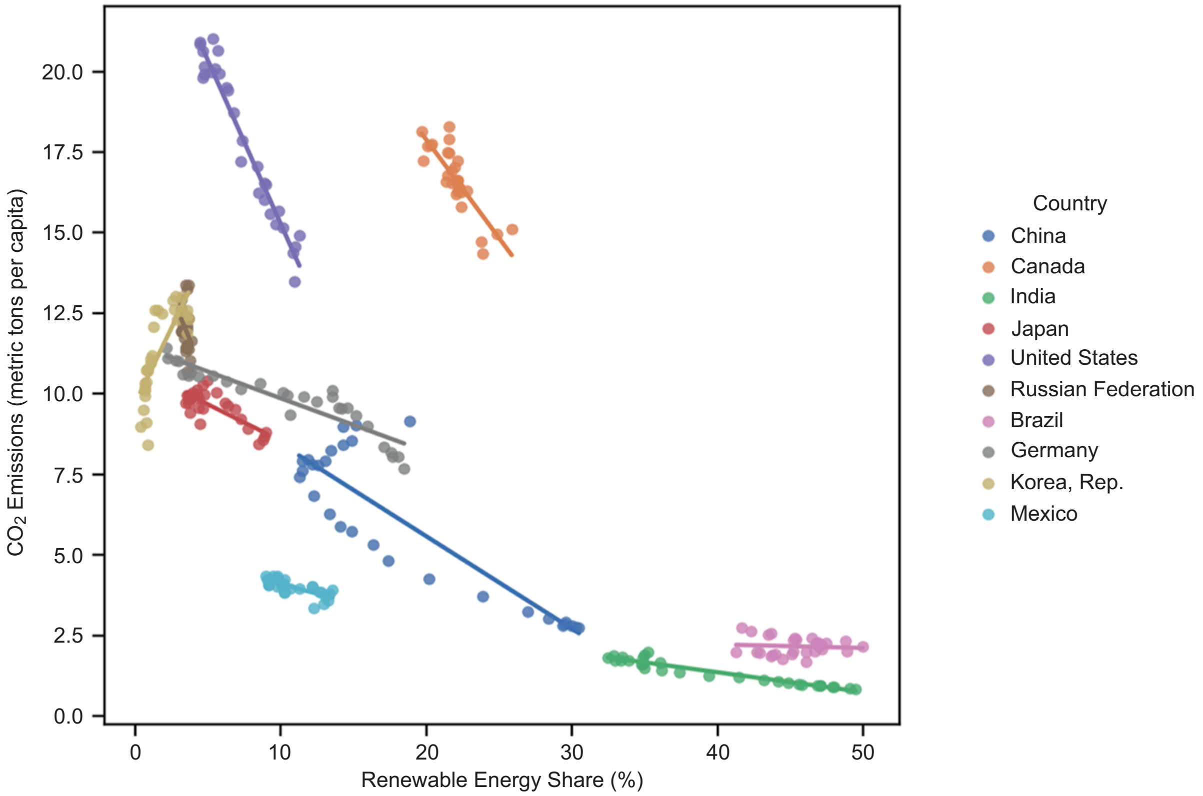

Fig. 2. CO_2 vs renewable energy
Source: Author's own plot based on World Bank data.

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but deeply embedded in institutional, economic, and infrastructural systems that resist rapid substitution. As shown in Fig. 2, the association between renewable energy share and CO_2 emissions across countries is far from uniform. Some high-emitting countries remain near the top of the emissions scale despite considerable renewable deployment, emphasizing the presence of system inertia, rebound effects, and policy misalignment. This complexity suggests that increasing renewable energy investment, while necessary, is not sufficient to guarantee decarbonization in structurally carbon-dependent economies.

Institutional limits in high emitters

Institutional quality is frequently cited as a significant determinant of environmental performance. However, its capacity to reduce emissions is highly context-dependent in high-emitting economies. Empirical evidence suggests that even measurable improvements in governance indicators, such as regulatory quality or control of corruption not necessarily convert into sustained emissions reductions. This disjuncture stems from what has been termed "governance fatigue": a condition in which environmental institutions become overburdened, co-opted, or politically constrained (Demiral et al., 2021; Shen et al., 2020). In carbon-intensive economies, institutional incentives often prioritize economic output, energy reliability, and employment over emissions mitigation. As a result, governance structures may nominally improve while remaining functionally misaligned with environmental goals.

Furthermore, regulatory capture by fossil fuel interests, weak enforcement capacity, and fragmented policy implementation contribute to a gap between formal institutional performance and actual environmental outcomes (Levin et al., 2012; Sovacool, 2016). In some cases, environmental regulations are symbolic or performative, adopted primarily to meet international expectations or attract foreign

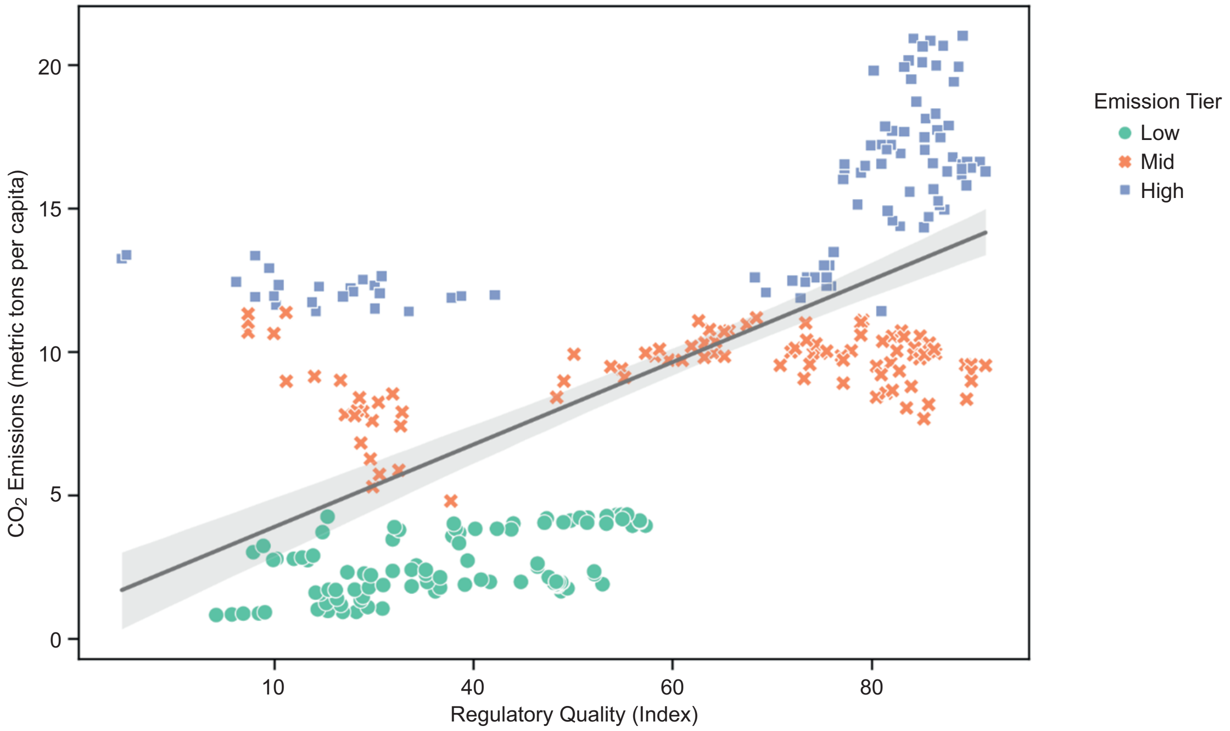

Fig. 3. CO_2 vs regulatory quality by emission tier
Source: Author's own plot based on World Bank data.

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funding, while leaving the domestic political economy undisturbed. This helps explain why institutional progress tends to exhibit diminishing marginal effects on emissions at higher levels of income or industrialization. The relationship may be nonlinear, with institutional quality exerting a stronger influence in low- and mid-emission situations, while becoming muted or distorted in high-emission settings due to entrenched interests and structural inertia. Recognizing this pattern is critical to understanding the limited mitigation leverage of governance reforms in countries that remain structurally locked into carbon-intensive development. As shown in Fig. 3, regulatory quality has a clearer association with lower emissions in low and mid-tier emitters, while its effect diminishes in the high-emissions tier. This supports the hypothesis of governance fatigue and diminished institutional efficacy in structurally locked-in economies.

MATERIALS AND METHODS

Data Source and Sample

This study uses annual panel data covering the period from 1995 to 2023, sourced from the World Bank's World Development Indicators. The dataset comprises ten of the world's highest cumulative CO_2-emitting countries over the study period: China, the United States, India, Russia, Japan, Germany, South Korea, Canada, Brazil, and Mexico. These countries were selected due to their outsized contribution to global carbon dioxide emissions and their structural significance in global production and energy systems. All variables used in the analysis are described in Table 1, which provides their acronyms, definitions, and sources. The dataset is log-transformed where applicable to reduce heteroskedasticity and improve interpretability. The selected variables reflect the study's focus on industrial structure, policy quality, technological inputs, and demographic dynamics.

Table 1. Variables description and data source

Variable	Acronyms in the equations	Detail	Source
Foreign direct investment	FDI	Net inflows % of gross domestic product (GDP)	World Bank (2025); https://data.worldbank.org/
Carbon dioxide emissions	CO_2	per capita (t CO_2e/capita)	World Bank (2025); https://data.worldbank.org/
Research and development expenditure	R&D	% of GDP	World Bank (2025); https://data.worldbank.org/
Renewable energy consumption	REC	% of total final energy consumption	World Bank (2025); https://data.worldbank.org/
Regulatory Quality	RQ	Percentile Rank	World Bank (2025); https://data.worldbank.org/
Population growth rate	POPG	Annual growth %	World Bank (2025); https://data.worldbank.org/
Manufacturing, value added	MANU	% of GDP	World Bank (2025); https://data.worldbank.org/

Source: World Bank.

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Theoretical framework and model specification

The selection of variables in this study is informed by established theoretical perspectives on the structural and institutional drivers of carbon dioxide emissions in high-emitting economies. Foreign direct investment influences emissions through two opposing views. According to Ecological Modernization Theory, FDI promotes cleaner production by supporting the adoption of advanced technologies. In contrast, the Pollution Haven Hypothesis suggests that multinational firms may shift pollution-intensive activities to countries with weaker environmental oversight, thereby increasing emissions (Cole, 2004).

Research and development expenditure reflect the capacity for technological advancement. Drawing from Technology Diffusion Theory (Rogers, 1962), it is expected that increased investment in R&D improves energy efficiency and supports the creation of low-carbon technologies (Popp, 2002). Renewable energy consumption is based on Energy Transition Theory (Sovacool, 2016), which emphasizes the gradual shift away from fossil fuels. A higher share of renewables in the national energy mix is expected to reduce reliance on carbon-intensive sources, thereby lowering emissions.

Regulatory quality is linked to Institutional Theory (North, 1990), which shows the importance of effective rules and enforcement systems. Higher regulatory quality supports environmental protection by ensuring the implementation and monitoring of policies designed to reduce emissions. Population growth is associated with increasing environmental pressure. Drawing on Malthusian Theory (Malthus, 1798), a growing population leads to higher demand for food, energy, and land, which may intensify environmental degradation. This idea is further extended by the IPAT identity (Ehrlich & Holdren, 1971), which conceptualizes environmental impact as a product of population, affluence, and technology. In rapidly urbanizing and industrializing economies, higher population growth typically contributes to rising emissions through increased energy use, infrastructure development, and resource consumption. These theoretical foundations support the inclusion of variables selected for the empirical analysis. The baseline model in Equation 1.

$$CO2_{it} = \alpha_i + \beta_1 MANU_{it} + \beta_2 POPG_{it} + \beta_3 RQ_{it} + \beta_4 REC_{it} + \beta_5 FDI_{it} + \beta_6 R\&D_{it} + \varepsilon_{it}) \tag{1}$$

Where CO_{2it} represents per capita carbon dioxide emissions for country *i* at time *t*. For estimation purposes, CO_2, MANU, REC, RQ, and R&D are expressed in logarithmic form, while FDI and POPG remain at levels due to the nature of their measurement. Equation (1) reflects the structural relationship estimated using both the PMG and DCCE techniques.

In Equation 1, manufacturing value added is used as a proxy for industrialization because it reflects the contribution of industrial activities to the economy. Regulatory quality represents policy measures, capturing the effectiveness of governance and regulatory frameworks. These methods capture both long- and short-run dynamics, while accounting for shared shocks and interdependence among countries in the sample. In addition to the main explanatory variables, the study includes an interaction term between foreign direct investment and regulatory quality (FDIRQ) to examine how the institutional environment influences the environmental impact of foreign investment. This interaction is estimated only within the PMG framework. Its inclusion helps assess whether stronger regulatory systems amplify or reduce the emissions effects of FDI. A positive coefficient on this term suggests that emissions rise with FDI even when regulatory quality improves, potentially indicating weak enforcement or investment patterns that remain carbon-intensive despite better institutions. The specification includes the interaction term FDIRQ = (FDI × RQ) to capture conditional effects of institutional quality on FDI-driven emissions.

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Cross-sectional dependence test

This study employed Breusch and Pagan (1980), Pesaran (2007), Pesaran et al. (2008), and Pesaran et al. (2004) to assess whether there are any interdependencies among the selected countries in the dataset. This methodological rigor enhances the reliability of the results. It provides a deeper understanding of the interconnected dynamics among the selected countries, contributing to a more accurate understanding of the determinants of carbon emissions in high-emitting economies. The Pesaran (2007) cross-sectional dependence (CD) test suits large panel datasets. This test accounts for potential interdependencies across countries, ensuring the estimates are not biased by omitted correlations among the panel units; however, the Pesaran CD test is in Equation 2.

$$CD = \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij} \xrightarrow{d} N(0,1) \quad (2)$$

Where CD represents the cross-sectional dependence statistic, T is the time, N is the number of cross-sections, and $\hat{\rho} ij$ is the sample correlation coefficient between cross-sections *i* and *j*. However, the Breusch and Pagan (1980) Lagrange Multiplier (LM) test is utilized as a foundational method to detect cross-sectional dependence in panels with a moderate number of cross-sectional units in Equation 3.

$$LM = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} T_{ij} \hat{\rho}_{ij}^2 \sim \chi^2_{\frac{N(N-1)}{2}} \quad (3)$$

The LM follows a chi-square distribution with $\frac{N(N-1)}{2}$ degrees of freedom. Conversely, to address potential limitations of the Breusch and Pagan LM test in larger panels, the study applies the Pesaran et al. (2008) Lagrange Multiplier (LM) test for cross-sectional dependence. This test refines the original LM methodology, making it robust for panels with a large cross-sectional dimension compared to the time dimension. By incorporating this test, the study ensures a more reliable detection of interdependencies, even in datasets with many countries represented by 4.

$$LM_{adj} = \sqrt{\frac{2}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{(T-K)\hat{\rho}_{ij}^2 - \mu_{Tij}}{\sqrt{v_{Tij}}} \xrightarrow{d} N(0,1) \quad (4)$$

Where K shows the number of regressors, μ is the bias-corrected mean, and v is the variance of T_{ij}.

Panel stationarity test

The study employed Pesaran's (2007) panel unit root framework to examine the stationarity properties of the variables while accounting for cross-sectional dependence. This approach extends traditional unit root methods by incorporating cross-sectional averages of lagged levels and first differences into the regression, making it appropriate for panels where countries are interconnected through common shocks or global factors. The framework builds on Pesaran et al. (2004), who introduced the Cross-Sectionally Augmented Dickey-Fuller (CADF) and Cross-Sectionally Augmented IPS (CIPS) tests. These tests address the limitations of earlier first-generation unit root tests that assume cross-sectional independence. By including cross-sectional averages, the CADF and CIPS methods effectively control for unobserved common factors that may drive correlations across panel units. The CIPS statistic is calculated as the average of individual CADF statistics across all countries, in Equation 5.

$$CIPS = \mathrm{N}^{-1} \sum_{i=1}^{N} CADF_i \quad (5)$$

Panel cointegration

The study employs the cointegration techniques of Kao (1999) and Westerlund (2005) to examine the long-run equilibrium relationships among the variables. The Kao test, developed for panel data, extends the Engle–Granger two-step framework and assumes homogeneity in the cointegration

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vector across cross-sectional units. This approach is beneficial for panel datasets with balanced structures, as it tests for cointegration by examining the residuals of the estimated panel regression, as indicated in Equation 6.

$$y_{it} = \beta_i t + \beta_{1it} x_{1it} + \beta_{2it} x_{2it} + \cdots + \beta_{kit} x_{kit} + \epsilon_{it} \tag{6}$$

Where the dependent variable y_{it} and the explanatory variables $x_{1it}, x_{2it}, \ldots, x_{kit}$. The individual-specific coefficients $\beta_i t$, β_{1it}, β_{2it}, and β_{kit} accommodate potential variations in the relationship across entities within the panel. In contrast, the Westerlund (2005) test investigates cointegration by directly testing for error correction in individual panel members rather than relying solely on residual-based procedures. This method is robust to cross-sectional dependence and allows for heterogeneity in the adjustment process across countries. The general specification is in Equation 7.

$$y_{it} = a_i + \beta X_{it} + u_{it} \tag{7}$$

y_{it} is the dependent variable,
X_{it} is a vector of independent variables,
β is the cointegration vector (representing the long-run relationship between y_{it} and X_{it}),
a_i is the individual-specific effect (fixed effects for each country or cross-section),
u_{it} is the residual (the error term).

Panel causality test

The study applies the Dumitrescu and Hurlin (2012) panel causality test to examine the direction of causal relationships among the variables within a heterogeneous panel framework. This approach is efficient for datasets where heterogeneity exists across cross-sectional units, allowing for variations in causal dynamics between countries. Unlike the traditional Granger causality test, the Dumitrescu and Hurlin procedure accommodates both cross-sectional dependence and heterogeneity for panels with diverse economic structures. The method computes individual Wald statistics for each cross-section and then aggregates them to obtain a panel-level statistic. This provides a comprehensive view of both country-specific and overall causal relationships among the variables. The model is in Equation 8.

$$Y_{i,t} = a_i + \sum_{p=1}^{p} \beta_{i,p}\, \Upsilon_{i,t-p} + \sum_{p=1}^{p} \Upsilon_{i,p} X_{i,t-p} + \varepsilon_{i,t} \tag{8}$$

where:
i – index for cross-sectional units (countries),
t – time period,
p – number of lags included in the model,
a_i – individual-specific fixed effects,
$\beta_{i,p}$ – coefficients for the lagged values of $Y_{i,t}$,
$\Upsilon_{i,p}$ – coefficients for the lagged values of $X_{i,t}$ indicating the causal effect of X on Y,
$\varepsilon_{i,p}$ – error term.

The coefficients $\beta_{i,p}$ and $\Upsilon_{i,p}$ are allowed to vary across cross-sectional units (i), capturing individual-specific dynamics.

$\boldsymbol{H_0}$: $0 \forall i =$ (No causality from X to Y in any cross-sectional unit).

$\boldsymbol{H_1}$: $\Upsilon_{i,p} \neq 0$ for at least one (i) (There is causality from X to Y in at least one cross-sectional unit).

Estimation Approach

This study employs a combination of the pooled mean group estimator and the dynamic common correlated effects model to test the determinants of carbon dioxide emissions in high-emitting economies. These methods are selected to account for both short-run heterogeneity across countries and long-run relationships, while also addressing cross-sectional dependence. The PMG estimator, introduced by Pesaran et al. (1999), estimates both short- and long-run relationships. It allows short-run coefficients, intercepts, and error variances to differ across countries while assuming that long-run coefficients are homogeneous. This approach is essential for economies that react differently in the short term but exhibit similar long-run emission patterns. The PMG model is in Equation 9.

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$$y_{it} = a_i + \sum_{j=1}^{p} \beta_{ij}\, y_{it-j} + \sum_{j=1}^{p} \delta_{ij}\, K_{it-j} + \mu_{it} \tag{9}$$

Where y_{it} is the dependent variable, a_i is the constant term, β_{ij} is the lag coefficient of the explained variable y_{it-j}, Q_{it-j} represents the independent variables with δ_{ij} as their corresponding coefficients, and ε_{it} indicates the error term in the estimated model in the PMG-ARDL.

To address cross-sectional dependence, the study uses the dynamic common correlated effects model, developed by Chudik and Pesaran (2015). This approach includes lagged cross-sectional averages of the dependent and independent variables to account for unobserved common shocks and global spillovers, such as energy price fluctuations or multilateral climate initiatives. The DCCE model is in Equation 10.

$$y_{it} = \alpha_i + \sum_{j=1}^{k} \emptyset_{ik}\, y_{it-k} + \sum_{j=1}^{k} \theta_{ik}\, Q_{it-k} + \sum_{j=1}^{k} \beta_{ik}\, \mathrm{P}_{it-k} + \varepsilon_{it} \tag{10}$$

Where P_{it-k} is the lagged cross-sectional averages, y_{it} indicates the explained variable, $\emptyset_{ik}\, y_{it-k}$ is the lagged of the dependent variable, $\theta_{ik}\, Q_{it-k}$ represents the explanatory variables.

In addition to the PMG and DCCE models, this study employs quantile regression (QR) by Koenker and Bassett (1978) to test how explanatory variables influence different points in the distribution of carbon dioxide emissions. Unlike mean-based estimators, QR captures the heterogeneous effects of drivers across countries with low, medium, and high emission levels. This approach complements the PMG and DCCE analyses by showing whether variables such as FDI, renewable energy consumption, and regulatory quality have stronger or weaker effects depending on the emission intensity of a country. The quantile regression model is in Equation 11.

$$Q_\tau(Y/X) = X\beta_\tau + \epsilon_\tau \tag{11}$$

Where;

$Q_\tau(Y/X)$ is the τ-th conditional quantile of the dependent variable Y,

X is the vector of the explanatory variables,

β_τ is the vector of coefficients estimated for quantile τ,

$\in_\tau$ is the error term.

By integrating QR with PMG and DCCE, the study provides a robust framework to capture both average long-run and short-run relationships across countries (through PMG and DCCE) and heterogeneous distributional effects (via QR). This ensures a more comprehensive understanding of how structural and institutional factors drive emissions in high-emitting economies.

RESULTS

Fig. 4 illustrates per capita CO_2 emissions for selected countries from 1995 to 2023, showing diverse trends influenced by industrial activity, energy transitions, and policy decisions. While some countries show long-term declines, others exhibit upward or fluctuating trends, with a significant increase in emissions for several nations in the years following the COVID-19 pandemic. China experienced a significant rise in per capita emissions during its rapid industrialization phase from the early 2000s to around 2015, after which emissions began to stabilize due to investments in renewable energy and energy efficiency. However, emissions increased again after 2020, extending into 2023, mainly showing a surge in industrial activity and energy demand during the post-pandemic economic recovery. India, though maintaining the lowest emissions per capita among the countries, shows a steady upward trend that continues through 2023, driven by industrial growth and increasing energy consumption.

The United States exhibits a long-term decline in emissions starting from 2007, indicating improvements in energy efficiency and a shift toward cleaner energy sources. However, there is a slight upward trend in emissions after 2020, extending into the

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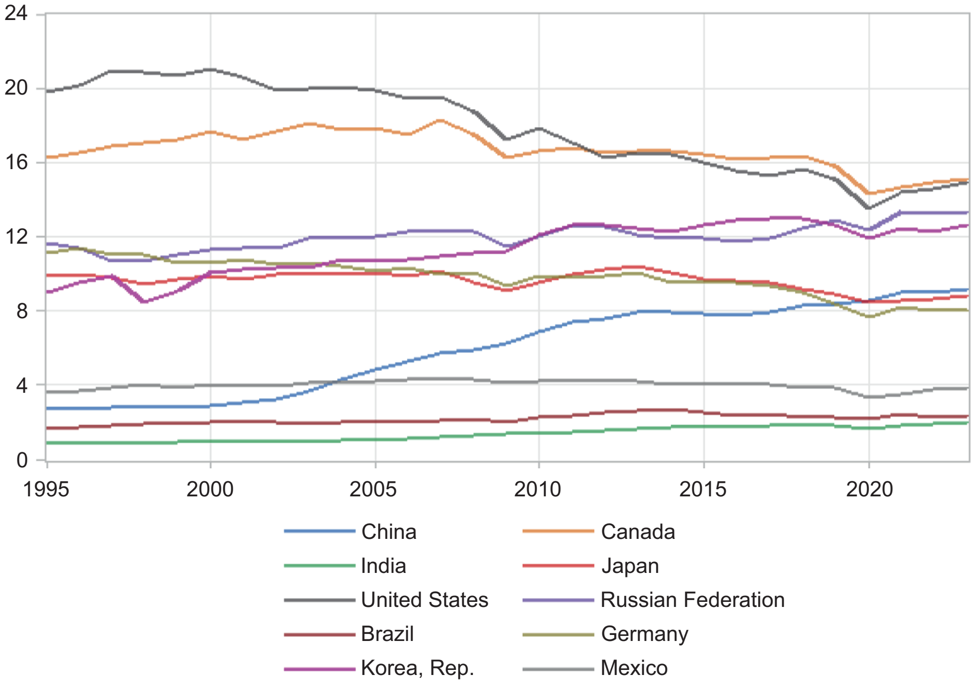

Fig. 4. CO_2 emission trend in the selected countries from 1995 to 2023
Source: Author's own plot based on World Bank data.

post-pandemic period, potentially due to increased transportation and industrial activity. Canada, with relatively stable but high emissions throughout, also shows an increase after 2020, due to the recovery of energy-intensive sectors.

Germany demonstrates a steady and sustained decline in emissions, showing its robust renewable energy policies and commitment to reducing carbon output. This downward trend continues through 2023, showing resilience even during periods of economic recovery. Brazil and Mexico, with relatively low emissions due to significant reliance on renewable energy sources, maintain stable trends over the period, including after 2020. South Korea, which had seen emissions rise until around 2015 before stabilizing, shows an increase post-2020 through 2023, driven by industrial recovery and heightened energy demands. Japan, which experienced a slight decline in emissions due to energy policy shifts following the Fukushima disaster, exhibits a stabilization or minor increase in emissions after 2020, extending into 2023.

Table 2 shows the descriptive statistics of the variables. Carbon dioxide emissions per capita show moderate average levels with some variation. The distribution is negatively skewed, suggesting that a subset of economies emits substantially less, displaying structural differences in industrialization, energy composition, and environmental regulation.

Manufacturing value-added exhibits low variability and a symmetric distribution, indicating consistent sectoral contributions across countries. While close to symmetric, population growth reveals positive and negative values, displaying diverse demographic trends such as ageing, migration, and socio-economic pressures in certain regions. Regulatory quality is more varied, with a left-skewed distribution pointing to the prevalence of weaker governance in several economies. Renewable energy consumption shows wide dispersion, driven by differences in infrastructure, policy commitment, and resource availability. Its negative skew suggests that higher adoption levels are more common, though some economies remain significantly behind.

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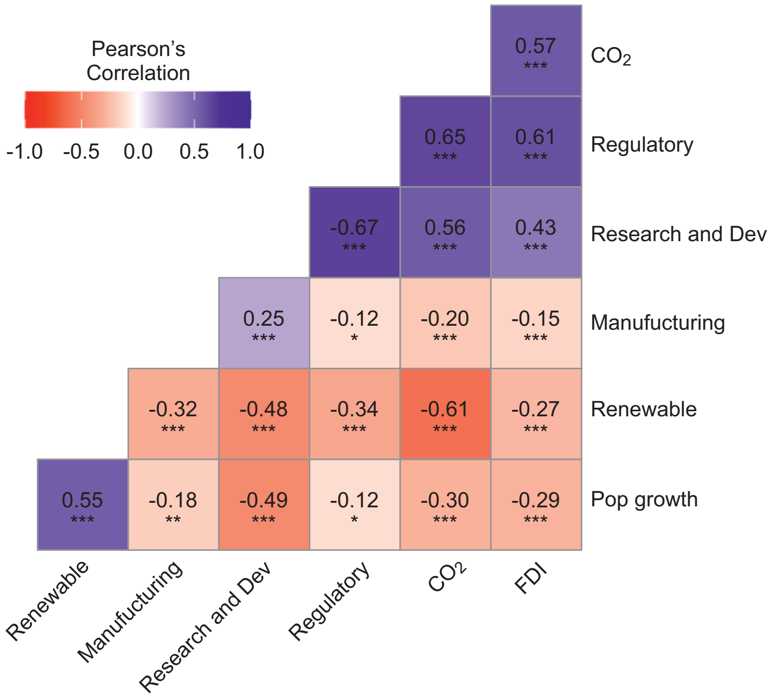
Table 2. Descriptive statistics

	lnCO$_2$	lnManu	POPG	lnRQ	lnREC	FDI	lnR&D
Mean	1.920	2.839	0.671	3.896	2.311	1.704	1.827
Median	2.273	2.863	0.725	4.008	2.379	1.285	1.733
Maximum	3.045	3.479	2.932	4.515	3.912	6.296	4.958
Minimum	-0.187	2.195	-1.853	1.551	-0.916	-0.632	0.149
Std. Dev.	0.857	0.333	0.623	0.549	1.097	1.444	1.076
Skewness	-0.790	-0.006	-0.034	-0.865	-0.437	0.906	0.448
Kurtosis	2.441	2.034	3.384	3.595	2.630	3.122	2.429
Sum	557	823	194.6	1130	670.4	494.2	529.9
Obs	290	290	290	290	290	290	290

Source: Author's own calculations.

FDI inflows display substantial variation, with a strong positive skew due to exceptionally high inflows in a few cases. These may correspond to periods of significant capital attraction or large investment deals. Similarly, research and development investment is unevenly distributed, with higher spending concentrated in a small group of innovation-led economies.

The correlation matrix in Fig. 5 reveals the associations among the study variables. Carbon dioxide emissions are positively correlated with regulatory quality, research and development expenditure, and manufacturing. These associations suggest that countries with stronger regulatory systems, higher innovation intensity, and greater



ns p > =0.05; * p < 0.05; ** p < 0.01; and *** p < 0.001

Fig. 5. Pearson correlation coefficients for the studied variables
Source: Author's own plot based on World Bank data.

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industrial output tend to experience higher levels of carbon emissions. Conversely, emissions are negatively associated with renewable energy consumption, population growth, and foreign direct investment, indicating that increased reliance on clean energy, demographic expansion, and international capital inflows are linked to lower emissions.

Regulatory quality exhibits a strong positive association with research and development, indicating that well-governed economies tend to invest in innovation. It also has a weaker positive association with manufacturing and a negative correlation with renewable energy consumption. Research and development is negatively associated with renewable energy, manufacturing, and population growth, implying that countries prioritizing technological advancement may not necessarily achieve emission reductions unless such investments are directed toward low-carbon innovations. Renewable energy consumption is negatively correlated with all other variables except emissions, suggesting its distinct role in mitigating environmental degradation. Population growth shows significant negative relationships with research and development, regulatory quality, and foreign direct investment, indicating structural differences in countries with higher demographic expansion.

Cross-section dependence test

The cross-sectional dependence and slope of the homogeneity tests presented in Table 3 reveal significant interdependence among the selected countries. The Breusch-Pagan LM test strongly rejects the null hypothesis of no cross-sectional dependence, indicating that shocks or policy changes in one country are likely to affect others. Similarly, the Pesaran scaled LM test, which corrects for potential bias when the cross-sectional dimension is large relative to the periods, confirms the presence of cross-sectional dependence. This reinforces the conclusion that the countries in the sample are not independent but subject to shared external influences or spillover effects. The Pesaran CD test further supports these findings, proving that the cross-sectional units are interconnected. The slope of the homogeneity test results shows significant evidence against the null hypothesis of slope homogeneity. This outcome indicates differences in the slopes across the units in this study, implying that the relationship between variables is not uniform across the entire sample.

Table 3. Cross-sectional dependence and Slope of homogeneity test results

Test	Statistic
Cross-sectional dependence test	
Breusch-Pagan LM	208.5***
Pesaran scaled LM	17.24***
Pesaran CD	4.054***
Slope of homogeneity test	
Delta	9.983***
Delta Adj.	12.021***

*** 1%, significance level

Source: Author's calculations.

Stationarity test

The CIPS unit root test results in Table 4 show the properties of the variables under study. The results reveal non-stationarity in their levels for

Table 4. CIPS unit root results

Variable	Level	Constant	Constant & Trend
FDI	0	-2.284	-2.675
ΔFDI	1	-6.340***	-5.881***
$\ln CO_2$	0	-1.800	-2.819
$\Delta \ln CO_2$	1	-4.772***	-4.646***
lnManu	0	-2.138	-2.442
ΔlnManu	1	-4.322***	-4.612***
lnREC	0	-0.970	-2.348
ΔlnREC	1	-4.269***	-4.821***
lnRQ	0	-1.703	-2.754
ΔlnRQ	1	-5.131***	-5.128***
POPG	0	-2.315	-2.888**
ΔPOPG	1	-4.205***	-3.991***
lnR&D	0	-1.795	-1.778
ΔlnR&D	1	-3.727***	-4.017***

*** 1%, ** 5%, significance level

Source: Authors calculations.

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carbon dioxide emissions, manufacturing value-added, renewable energy consumption, regulatory quality, population growth, FDI, and research and development. However, when analysed at their first differences, these variables exhibit stationarity. The requirement for differencing in variables such as CO_2 and REC indicates that environmental and energy-related measures are shaped by gradual transitions, such as the adoption of renewable technologies or regulatory changes in emissions policies. Similarly, the non-stationarity of RQ and R&D emphasizes the evolving nature of governance and innovation, potentially influenced by institutional reforms or increased global competition in research capabilities.

Panel cointegration test

The Kao and Westerlund cointegration tests in Table 5 produce mixed results. While some test statistics provide evidence of cointegration, others do not. The augmented Dickey-Fuller t-statistic and the Dickey-Fuller t-statistic show the presence of cointegration. In contrast, the modified Dickey--Fuller t-statistic and the unadjusted versions do not provide strong evidence in favor of cointegration. The Westerlund cointegration test, based on the variance ratio, provides significant evidence supporting the presence of cointegration. This outcome indicates a long-run relationship among the variables.

Table 5. Kao and Westerlund cointegration test

Kao cointegration	Statistic
Modified Dickey-fuller t	-1.394*
Dickey Fuller t	-2.205**
Augmented Dickey-fuller t	-2.764***
Unadjusted modified Dickey-fuller t	0.578
Unadjusted Dickey-fuller t	1.344*
Westerlund cointegration	
Variance ratio	-2.314***

*** 1%, ** 5%, *10%, significance level
Source: Authors calculations.

Empirical estimated results

Table 6 indicates the outcome of the PMG-ARDL estimation. In the long run, an expansion in manufacturing value added leads to an increase in carbon dioxide emissions. This relationship reflects the emission-intensive nature of industrial activity in the high-emitting countries analyzed, where production processes remain heavily reliant on fossil fuels. Increases in manufacturing activity are associated with higher emissions, reaffirming the short-run impact of industrial expansion on environmental outcomes. A rise in renewable energy consumption, however, significantly reduces emissions, supporting the effectiveness of transitioning away from carbon-intensive energy sources. Growth in renewable energy consumption also results in a reduction in emissions in the short run, demonstrating the immediate benefits of clean energy integration. Continued reliance on fossil fuels and structural barriers to scaling renewable technologies may limit its impact.

Table 6. Estimated coefficients from the PMG-ARDL model

Long run	Coefficient	Std. Err.	t-statistics	p-value
lnManu	0.570	0.233	2.441	0.016
lnREC	-0.775	0.062	-12.37	0.000
lnRQ	0.060	0.066	0.900	0.369
FDI	-0.641	0.154	-4.162	0.000
lnR&D	0.132	0.042	3.120	0.002
POPG	-0.611	0.064	-9.412	0.000
FDIRQ	0.155	0.035	4.361	0.000
Constant	0.244	0.079	3.076	0.002
Short Run				
ECT (-1)	-0.113	0.036	-3.149	0.002
ΔlnManu	0.169	0.069	2.427	0.016
ΔlnREC	-0.377	0.134	-2.809	0.005
ΔlnRQ	0.028	0.083	0.346	0.729
ΔFDI	-0.088	0.113	-0.781	0.435
ΔlnR&D	-0.093	0.040	-2.313	0.021
ΔPOPG	0.096	0.053	1.796	0.074
Δ FDIRQ	0.018	0.027	0.663	0.507

Source: Author's calculations.

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Foreign direct investment is also associated with lower emissions, indicating that capital inflows may be contributing to cleaner production techniques or supporting sectors with relatively lower environmental footprints. While some investments may support green technologies, others reinforce emissions-intensive activities, resulting in a neutral total effect. Research and development expenditure, on the other hand, is linked to an increase in emissions over time. This outcome may indicate that innovation efforts in these economies are more focused on economic or industrial advancement rather than decarbonization. Additionally, short-term increases in research and development expenditure are associated with lower emissions, pointing to the possibility that some innovation initiatives may produce rapid environmental improvements before their broader economic effects are fully realized. Population growth contributes to a decline in per capita emissions, possibly due to shifts in demographic structure, energy efficiency improvements, or scale effects.

Moreover, the interaction between regulatory quality and FDI (FDIRQ) reveals a positive coefficient, indicating that the ability of foreign investment to reduce emissions is enhanced when environmental institutions are functioning more effectively. This shows the importance of pairing effective governance with proactive environmental policies to balance economic growth with sustainability. In the short term, the negative and statistically significant adjustment coefficient confirms that the system corrects toward its long-run equilibrium.

Table 7 shows the results from the DCCE model. In the long run, regulatory quality is positively associated with lower carbon dioxide emissions, indicating that improvements in institutional performance are linked to reductions in environmental pressure. Renewable energy consumption also contributes to long-run emission reduction, consistent with the displacement of carbon-intensive sources in favor of cleaner alternatives. Additionally, population growth shows a negative association with emissions over the long term. This may reflect efficiency gains or demographic structures that result in relatively lower emissions per capita as the population increases. In the short run, the lagged dependent variable is positive and statistically significant, indicating that current emissions are partially influenced by past values. Regulatory quality continues to have a negative effect in the short term, suggesting that institutional improvements produce immediate environmental changes. Renewable energy consumption also lowers emissions in the short run, reinforcing its role in emission dynamics. The error correction term is negative and significant, confirming the presence of a stable long-run relationship and indicating that deviations from equilibrium are corrected gradually.

Table 7. Estimated coefficients from the DCCE

Long run	Coefficient	Std. Err.	t-statistics	p-value
FDI	0.004	0.005	0.01	0.998
lnManu	0.003	0.005	0.72	0.474
POPG	-0.048	0.028	-1.71	0.087
lnR&D	-0.001	0.042	-0.03	0.973
lnRQ	0.003	0.001	2.49	0.013
lnREC	-0.045	0.151	-3.00	0.003
Short Run				
ΔlnCO2	0.140	0.06	2.26	0.024
ΔlnManu	0.003	0.005	0.65	0.514
ΔFDI	0.003	0.004	0.09	0.931
ΔlnRQ	0.002	0.001	2.51	0.012
ΔlnREC	-0.033	0.008	-4.42	0.000
ΔlnR&D	-0.001	0.033	-0.02	0.998
ΔPOPG	-0.034	0.020	-1.71	0.087
ECT (-1)	-0.859	0.062	-13.80	0.000

Source: Author's calculations.

Table 8 indicates the distributional effects of the explanatory variables across different quantiles of CO_2 emissions. FDI shows a generally positive relationship with emissions, with its influence increasing in higher quantiles. This indicates that in countries with greater emission levels, foreign investment contributes more to environmental degradation when directed toward carbon-intensive sectors. Manufacturing value-added is negatively associated with emissions in the lower quantiles, displaying that in less emission-intensive

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Table 8. Estimated coefficients of the distributional effects model

Variable	Qtl 0.1	Qtl 0.2	Qtl 0.3	Qtl 0.4	Qtl 0.5	Qtl 0.6	Qtl 0.7	Qtl 0.8	Qtl 0.9
FDI	-0.042	0.331**	0.488**	0.493**	0.770**	0.904***	1.094***	0.819***	0.691***
	(0.346)	(0.166)	((0.194)	(0.227)	(0.268)	(0.322)	(0.267)	(0.245)	(0.217)
	[-0.122]	[1.994]	[2.506]	[2.172]	[2.874]	[2.808]	[4.087}	[3.341]	[3.180]
lnManu	-0.382**	-0.413***	-0.405***	-0.415***	-0.468***	-0.410***	-0.378***	-0.366***	-0.357***
	(0.162)	(0.098)	(0.109)	(0.098)	(0.070)	(0.062)	(0.049)	(0.069)	(0.114)
	[-2.346]	[-4.176]	[-3.691]	[-4.226]	[-6.688]	[-6.605]	[-7.571]	[-5.256]	[-3.117]
POPG	0.962	0.755	0.791	0.975	1.880***	1.728***	1.914***	2.351***	1.530
	(0.771)	(0.64)	(0.708)	(0.710)	(0.461)	(0.420)	(0.547)	(0.702)	(1.663)
	[1.248]	[1.169]	[1.116]	[1.372]	[4.078]	[4.110]	[3.498]	[3.347]	[0.920]
lnR&D	2.401***	2.267***	2.058***	2.438***	2.270***	1.613***	0.789	0.049	0.983
	(0.264)	(0.233)	(0.241)	(0.265)	(0.386)	(0.534)	(0.537)	(0.438)	(1.020)
	[9.080]	[9.693]	[8.533]	[9.190]	[5.881]	[3.0196]	[1.469]	[0.111]	[0.964]
lnREC	-0.198***	-0.211***	-0.215***	-0.219***	-0.245***	-0.238***	-0.258***	-0.277***	-0.254***
	(0.049)	(0.019)	(0.022)	(0.021)	(0.019)	(0.022)	(0.028)	(0.023)	(0.039)
	[-3.973]	[-10.761]	[-9.683]	[-10.323]	[-12.358]	[-10.406]	[-9.205]	[-11.73]	[-6.377]
lnRQ	0.003	-0.020	-0.010	-0.020	-0.001	0.012	0.037*	0.063***	0.075***
	(0.044)	(0.018)	(0.020)	(0.016)	(0.016)	(0.018)	(0.020)	(0.019)	(0.019)
	[0.069]	[-1.103]	[-0.502]	[-1.238]	[-0.052]	[0.702]	[1.844]	[3.271]	[3.925]
Constant	10.651	13.24***	13.17***	13.74***	13.82***	13.79***	13.96***	15.495***	14.46***
	(5.490)	(1.287)	(1.256)	(1.073)	(1.286)	(1.312)	(1.341)	(1.393)	(2.812)
	[1.939]	[10.290]	[10.479]	[12.807]	[10.744]	[10.514]	[10.409]	[11.118}	[5.144]

*** 1%, ** 5% significance level
Source: Author's calculations.

economies, industrial development may involve efficiency gains or cleaner production methods. However, this effect becomes weaker in higher quantiles, where industrial output is more tied to energy-intensive activities.

Population growth has a positive impact on emissions, with its effect more evident in the upper quantiles. This shows that population increases lead to greater energy demand and resource consumption, especially in more urbanized and industrialized countries. R&D expenditure is positively related to emissions across quantiles, with a stronger effect in the lower range. This may reflect that early-stage innovation in low-emission countries is often linked to industrial expansion, which initially involves energy-intensive processes. In higher-emission economies, the influence of R&D becomes less effective, possibly due to existing adoption of more efficient technologies.

Renewable energy consumption consistently shows a negative relationship with emissions across all quantiles, with the effect becoming stronger in countries with higher emissions. This confirms that expanding the share of renewable energy reduces CO_2 levels more significantly where emissions are elevated. Regulatory quality has a positive and significant effect at the upper quantiles. This shows that in high-emission economies, improvements in governance may not sufficiently offset emissions from entrenched carbon-heavy sectors.

Robustness estimation

The robustness estimates using fully modified (FMOLS) ordinary least squares and dynamic least squares (DOLS) in Table 9 largely confirm the main findings from the panel ARDL models. The FMOLS estimates show that research and development expenditure is positively associated with carbon dioxide emissions at the 1% level, indicating that increased innovation spending is linked with rising emission levels in the sample. Renewable energy consumption has a negative and statistically

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Table 9. Estimated coefficients from the FMOLS and DOLS models

	FMOLS	DOLS				
Variable	Coefficient	Std.Error	t-statistic	Coefficient	Std.Error	t-statistic
lnManu	0.044	0.104	0.430	0.009	0.147	0.062
FDI	-0.043	0.103	-0.419	0.228	0.284	0.801
lnR&D	0.253***	0.029	8.679	0.221***	0.062	3.520
lnREC	-0.373***	0.037	-9.824	-0.224***	0.053	-4.166
lnRQ	0.149***	0.058	2.537	0.053	0.117	0.452
POPG	-0.196***	0.036	-5.394	-0.195***	0.054	-3.573
FDIRQ	0.013	0.024	0.534	-0.055	0.066	-0.837

***, 1%, significance level
Source: Author's calculations.

significant relationship with emissions, indicating that greater adoption of clean energy sources contributes to emission reduction. Population growth is also associated with a significant decline in emissions, and regulatory quality displays a positive and statistically significant effect in this specification. The DOLS results support the FMOLS findings for research and development, renewable energy consumption, and population growth. All three variables maintain their direction and significance at the 1% level, confirming the consistency of their influence on emissions across estimation techniques.

PANEL CAUSALITY TEST

The pairwise Dumitrescu-Hurlin panel causality test results in Table 10 show the causal relationships between CO_2 emissions and FDI, industrial, and policy variables, and interdependencies among these variables. The findings reveal bidirectional causality between CO_2 emissions and manufacturing value-added, showing a mutually reinforcing relationship. Manufacturing activity contributes to emissions through energy-intensive processes, while emissions may influence industrial strategies, such as

Table 10. Pairwise Dumitrescu-Hurlin causality test result

Null Hypothesis:	W-Stat.	Zbar-Stat.	p-value	Conclusion
lnManu ↛ lnCO_2	3.482	1.667	0.095	
lnCO_2 ↛ lnManu	6.023	4.971	0.000	Bidirectional
POPG ↛ lnCO_2	3.417	1.583	0.113	
lnCO_2 ↛ POPG	7.893	7.402	0.000	Unidirectional
lnRQ ↛ lnCO_2	4.053	2.409	0.016	
lnCO_2 ↛ lnRQ	2.790	0.767	0.442	Unidirectional
lnREC ↛ lnCO_2	3.131	1.211	0.225	
lnCO_2 ↛ lnREC	6.844	6.039	0.000	Unidirectional
FDI ↛ lnCO_2	2.535	0.436	0.662	
lnCO_2 ↛ FDI	3.894	2.203	0.027	Unidirectional
lnR&D ↛ lnCO_2	2.729	0.689	0.490	
lnCO_2 ↛ R&D	7.075	6.338	0.000	Unidirectional

Source: Author's calculations.

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shifts to cleaner production or regulatory responses. A similar bidirectional relationship between CO_2 emissions and research and development indicates that emissions spur innovation efforts aimed at mitigation, while technological advancements can alter emissions patterns. The results also show unidirectional causality in several relationships. CO_2 emissions homogeneously cause renewable energy consumption, regulatory quality, foreign direct investment, and population growth. This indicates that higher emissions drive responses in energy transitions, governance improvements, and economic activities. For example, increasing emissions may encourage greater renewable energy adoption and stricter governance measures. Conversely, while these variables respond to emissions, the reverse causality is not homogeneous across the panel, except in specific cases like RQ affecting emissions.

DISCUSSION

The empirical results provide comprehensive evidence on the determinants of carbon dioxide emissions across high-emitting economies, with consistent support for the role of industrial activity, renewable energy consumption, and institutional quality in shaping environmental outcomes. The findings from the PMG-ARDL, DCCE, quantile regression, and robustness estimations collectively reveal both linear and heterogeneous relationships between economic, technological, and governance variables and environmental degradation.

The PMG-ARDL results demonstrate that manufacturing expansion significantly increases carbon emissions in the long run, reaffirming the emission-intensive nature of industrial production in the analyzed economies. This aligns with existing evidence that manufacturing remains a major source of environmental degradation due to fossil-fuel dependence and limited technological upgrading (Emenekwe et al., 2023). The short-run elasticity further confirms that increases in manufacturing output are immediately reflected in higher emissions, emphasizing the persistence of industrial reliance on conventional energy sources.

Renewable energy consumption emerges as a robust determinant of emission reduction across all models. Both the PMG-ARDL and DCCE results confirm a negative and statistically significant long-run relationship, indicating that greater adoption of renewable energy mitigates environmental degradation by displacing carbon-intensive sources. The short-run effects are similarly negative and significant, indicating the immediate environmental benefits of clean energy integration. These findings are consistent with the literature emphasizing renewable energy's role in promoting sustainable growth through decarbonization (Ayhan et al., 2023; Bashir et al., 2023).

The role of FDI presents mixed patterns across the models. The PMG-ARDL results indicate that FDI contributes to emission reduction in the long run, implying that foreign capital inflows may promote cleaner technologies or environmentally efficient practices in the host countries. However, the distributional estimates reveal that the environmental impact of FDI becomes more adverse in higher emission quantiles, indicating that in economies with heavy industrial dependence, FDI tends to reinforce carbon-intensive activities. This dual behavior is consistent with the "pollution halo" and "pollution haven" hypotheses, indicating that the net effect of FDI depends on the sectoral composition and regulatory strength of the host country (Mohapatra et al., 2023).

The interaction between regulatory quality and FDI (FDIRQ) in the PMG-ARDL model is positive and significant, implying that environmental institutions enhance the emission-reducing effects of foreign investment. This interaction shows the importance of institutional capacity in ensuring that foreign capital supports sustainable objectives rather than exacerbating pollution (Demiral et al., 2021). In the DCCE framework, regulatory quality independently shows a significant negative effect on emissions, confirming that improved governance and policy enforcement are critical to long-term environmental sustainability. Nevertheless, the quantile regression results reveal that the effect of regulatory quality becomes positive at higher emission levels, implying that institutional improvements may not fully offset

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emissions in economies where fossil-fuel-based industries dominate. This shows that governance reforms alone are insufficient without simultaneous structural shifts toward clean production.

Research and development expenditure exhibit a complex relationship with emissions. In the PMG--ARDL and robustness models (FMOLS and DOLS), R&D is positively associated with emissions in the long run, indicating that innovation efforts are primarily directed toward industrial expansion rather than environmental sustainability. However, the short--run PMG-ARDL coefficient for R&D is negative, indicating that some innovation initiatives may yield immediate environmental improvements before their broader economic expansionary effects materialize. This finding supports the view that technological innovation initially intensifies industrial activity before transitioning toward cleaner technologies over time.

Population growth is consistently linked with emission reduction in the long run across the PMG-ARDL, DCCE, and robustness estimations. This unusual result may reflect scale effects and structural efficiency gains in high-density economies, where improvements in urban planning, public transport, and energy efficiency reduce per capita emissions (Bashir et al., 2023). However, the quantile regression results reveal that population growth contributes to higher emissions in upper quantiles, supporting evidence from Şanli et al. (2023) and Saqib (2022) that demographic expansion amplifies energy demand and environmental pressure in more industrialized and urbanized perspective.

The Dumitrescu–Hurlin panel causality results further substantiate these relationships by showing the directionality of effects among key variables. The bidirectional causality between CO_2 emissions and manufacturing value added implies a feedback mechanism where industrial growth drives emissions while environmental degradation, in turn, influences industrial adaptation and regulation. A similar two-way causality between emissions and R&D shows that higher pollution levels stimulate innovation aimed at mitigation, while technological progress subsequently affects emission patterns. Unidirectional causality from emissions to renewable energy, governance quality, FDI, and population growth indicates that environmental degradation acts as a catalyst for policy, economic, and demographic responses. This dynamic supports the notion that environmental pressures often trigger adaptive economic behavior and policy reforms toward sustainability.

These findings indicate that the path to emission reduction in high-emitting economies depends on the combined effectiveness of industrial transformation, renewable energy expansion, and institutional quality. While renewable energy and governance improvements show consistent environmental benefits, manufacturing activity and innovation remain key sources of emissions unless reoriented toward low-carbon production systems. The heterogeneity observed across emission levels emphasizes that policies must be tailored to each country's structural and institutional characteristics rather than applying uniform solutions.

CONCLUSIONS

This study investigates the determinants of carbon dioxide emissions across the ten highest-emitting economies from 1995 to 2023, using the pooled mean group estimator and the dynamic common correlated effects model. The analysis incorporates main variables, including manufacturing output, foreign direct investment, renewable energy consumption, regulatory quality, population growth, and research and development. Findings indicate that renewable energy consumption consistently reduces emissions in the long run, with stronger effects observed in economies with higher emission levels. Population growth reduces emissions in the long run, suggesting demographic-related efficiency gains, emphasizing the environmental pressures that accompany demographic expansion. Research and development expenditure contributes to higher emissions in lower-emission countries, showing innovation tied to industrial and energy-intensive growth. FDI alone reduces CO_2 emissions. The interaction between foreign direct

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investment and regulatory quality is significant, suggesting that the environmental outcome of foreign investment depends on the strength and enforcement of regulatory institutions. An expansion in manufacturing value added leads to an increase in carbon dioxide emissions in the long run.

Quantile regression results reveal that the magnitude and direction of variable effects vary across the emission distribution. Renewable energy consumption has a more substantial mitigating impact in high-emission settings. Regulatory quality, while positively associated with emissions at higher quantiles, indicates that improvements in governance alone may not offset emissions from carbon-dependent economic structures. These findings imply that expanding renewable energy infrastructure should remain central to emission reduction strategies.

Policy Implications

The empirical results of this study provide important details with clear policy implications for reducing carbon emissions in high-emitting economies. The findings indicate that industrial expansion, renewable energy use, institutional quality, foreign direct investment, and research and development each play distinct roles in shaping environmental outcomes. Building on these results, the following policy recommendations are proposed.

Firstly, since manufacturing value added is found to significantly increase carbon dioxide emissions in the long run, policymakers should prioritize industrial decarbonization through the adoption of energy-efficient technologies and cleaner production processes. Industrial policy should encourage firms to integrate low-carbon technologies, promote circular production systems, and adopt best practices for energy conservation. Fiscal incentives such as tax rebates or green subsidies could stimulate private sector participation in emission reduction initiatives.

Secondly, the consistent negative relationship between renewable energy consumption and emissions in both the short and long run emphasizes the need to scale up investment in renewable energy infrastructure. Governments should create stable and transparent regulatory frameworks that attract both domestic and foreign investment in solar, wind, and other clean energy sectors. Establishing long-term energy transition plans, coupled with supportive tariffs and financing mechanisms, will ensure continuity of renewable energy development and strengthen its contribution to emission reduction.

Additionally, the positive long-run association between research and development expenditure and emissions suggests that innovation in high-emitting economies is still oriented toward industrial expansion rather than sustainability. To correct this, innovation policies should redirect R&D funding toward low-carbon technologies. Governments can facilitate this shift by supporting university–industry partnerships focused on renewable energy, emission capture, and efficiency-enhancing technologies. Additionally, expanding intellectual property protection and providing targeted grants for green innovation would enhance the diffusion of clean production methods.

Conversely, although FDI shows potential to reduce emissions when coupled with strong regulatory frameworks, its distributional effects reveal that FDI can also worsen environmental degradation in higher-emission economies. Therefore, policymakers must align FDI policies with environmental objectives by enforcing stricter environmental standards for incoming investment projects. Investment promotion agencies should screen foreign projects for sustainability compliance and provide incentives for investors who adopt low-emission technologies or contribute to renewable energy sectors.

Furthermore, the evidence that population growth reduces per capita emissions in the long run but increases total emissions in more industrialized contexts calls for integrated urban and energy planning. Policymakers should anticipate demographic expansion by investing in efficient public transport, green buildings, and sustainable urban infrastructure to avoid locking economies into carbon-intensive development patterns. Energy use policies must be forward-looking, ensuring that population growth aligns with renewable energy deployment and energy efficiency improvements.

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Finally, the interaction between regulatory quality and FDI, as well as the strong long-run influence of institutional quality on emissions, highlights the central role of governance effectiveness. Strengthening institutional capacity, enhancing environmental monitoring, and improving enforcement mechanisms are significant to ensure that industrial and investment activities align with climate targets. Transparent and accountable institutions can foster investor confidence and drive long-term sustainable transitions.

The findings emphasize the importance of a coordinated policy strategy that simultaneously strengthens institutions, accelerates the energy transition, redirects innovation, and manages demographic and industrial pressures. High-emitting economies must integrate environmental governance into broader economic policy frameworks, ensuring that growth objectives are compatible with emission reduction goals. Only through coherent and sustained policy commitment can these economies achieve a balance between industrial competitiveness and environmental sustainability.

Limitations and Future Research

While this study provides robust evidence on the drivers of CO_2 emissions in the world's highest-emitting economies, it is not without limitations. First, although the PMG and dynamic common correlated effects (DCCE) estimators account for heterogeneity and cross-sectional dependence, the analysis remains limited to a fixed group of ten countries, which may constrain generalizability. Second, due to data limitations, the study does not disaggregate emissions by sector or energy source, which could help pinpoint the most carbon-intensive activities. Third, the use of annual data may obscure short-term fluctuations and policy shocks. Future research could expand the geographical scope to include emerging emitters, adopt a sector-specific or energy-type decomposition, and explore interactions between environmental regulations and fiscal or trade policy. Additionally, incorporating spatial econometric techniques may uncover deeper structural patterns in emission dynamics.

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