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Green transition, institutions and environmental efficiency in OECD economies

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ABSTRACT

The green transition is frequently framed as a primarily technological undertaking, yet its environmental payoff depends on the institutional and structural conditions under which clean-energy and innovation inputs are deployed. This paper develops an integrated green-transition and institutional–environmental-efficiency framework and tests it on an unbalanced panel of 38 OECD economies observed between 2000 and 2021. We distinguish two complementary outcomes-CO_2 emissions per capita, which capture environmental pressure, and energy intensity, which captures environmental efficiency-and estimate their determinants with two-way fixed-effects models corrected by Driscoll–Kraay standard errors that are robust to heteroskedasticity, serial correlation and cross-sectional dependence. The empirical strategy layers a baseline specification with an Environmental Kuznets Curve test on mean-centred income, institutional interaction models, a panel quantile analysis of distributional heterogeneity, and robustness checks using logistics performance and the individual governance indicators. Renewable energy consistently and significantly lowers CO_2 emissions across all specifications, whereas research and development, income and institutional quality operate more visibly through the energy-efficiency channel. The central contribution is evidence that institutional quality, though not a simple linear depressant of emissions, strengthens the environmental effectiveness of both renewable energy and innovation: all four institution-by-input interactions are negative and statistically significant. The findings portray the OECD green transition as jointly technological, structural and institutional, and imply that governance capacity should be treated as a multiplier that converts green-transition inputs into measurable environmental performance.

Keywords: Green transition, Renewable energy, Institutional quality, Energy intensity, Carbon emissions, OECD, Two-way fixed effects, Environmental efficiency, Green taxes.
JEL classification: Q43; Q56; Q58; O44; O17
Article type: Research Article.

INTRODUCTION

Few policy objectives command as broad a consensus among advanced economies as the decarbonisation of energy systems, and few have proved as difficult to translate into sustained environmental results. Members of the Organisation for Economic Co-operation and Development (OECD) have, over the past two decades, committed substantial public and private resources to the expansion of renewable energy, the financing of clean-technology research, and the construction of regulatory architectures intended to discipline carbon-intensive production. The aggregate trajectory is encouraging: average per-capita CO_2 emissions and average energy intensity have both trended downward since the early 2000s, while the renewable share of final energy consumption has risen markedly. Yet the headline averages conceal pronounced cross-country heterogeneity. Economies with comparable income levels and comparable nominal commitments to clean energy have realised

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strikingly different environmental outcomes, which suggests that the green transition cannot be reduced to the mechanical accumulation of renewable capacity or research spending. This paper takes that heterogeneity as its point of departure and argues that the environmental return on green-transition inputs is conditioned by the institutional and structural environment in which they operate. The intuition is straightforward but consequential. Renewable capacity must be integrated into grids, dispatched against incumbent fossil assets, and financed under credible long-horizon contracts; research must be diffused, commercialised and absorbed by domestic industry; and the entire apparatus must be coordinated by regulators whose commitments are believed by investors and firms. Each of these steps is mediated by the quality of governance-by government effectiveness, regulatory quality, the rule of law and the control of corruption. Where these capacities are strong, a given quantum of renewable energy or innovation should translate more fully into emission reductions and efficiency gains; where they are weak, the same nominal inputs may dissipate into implementation gaps, policy reversals and rent-seeking. Institutions, on this reading, are less a direct lever on emissions than a *multiplier* on the effectiveness of the levers that policymakers actually pull. The existing literature, while rich, has tended to examine the constituent relationships in isolation. A large body of work documents that renewable energy reduces carbon emissions; a parallel literature links research and development (R&D) and eco-innovation to improved energy efficiency; a third strand relates institutional quality and governance to environmental performance; and a fourth revisits the Environmental Kuznets Curve (EKC) and the nonlinear income–environment relationship. Comparatively few studies bring these channels into a single, internally consistent framework for advanced economies, and fewer still simultaneously (i) separate environmental *pressure* from environmental *efficiency*, (ii) test the nonlinear income effect, (iii) model institutions as a moderator of green-transition inputs rather than only as a direct regressor, and (iv) allow the effects to vary across the conditional distribution of environmental outcomes. The result is a fragmented evidence base that can describe the parts of the green transition but struggles to characterise the system. We address this gap with an integrated analysis of 38 OECD economies over 2000–2021. Two features define the contribution. First, we treat CO_2 emissions per capita and energy intensity as distinct but complementary outcomes-the former a measure of the environmental pressure a society exerts, the latter a measure of how efficiently it converts energy into economic value-and we show that the green transition reaches them through different channels. Second, we place institutional quality at the centre of the analysis not merely as a control but as a conditioning variable, and we test directly whether governance strengthens the environmental effectiveness of renewable energy and innovation. The empirical apparatus is designed for transparency and robustness: a two-way fixed-effects baseline with Driscoll–Kraay standard errors, an EKC specification on mean-centred income, institutional interaction models, a panel quantile analysis of distributional heterogeneity, and two families of robustness checks based on logistics performance and the individual governance indicators.

Research questions

Against this background, the study is organised around four questions:

Through which channels do renewable energy, innovation and the broader green-transition inputs shape environmental outcomes in OECD economies, and do those channels differ for environmental *pressure* (emissions) versus environmental *efficiency* (energy intensity)?

Is the income–emissions relationship in advanced economies linear, or is there evidence of a nonlinear, inverted-U tendency consistent with the Environmental Kuznets Curve?

Does institutional quality reduce emissions and energy intensity directly, or does its primary environmental role lie in *moderating* the effectiveness of renewable energy and R&D?

Are these relationships homogeneous, or do they vary across the conditional distribution of emissions and energy intensity-being stronger, for instance, among cleaner or among more energy-intensive economies?

Contributions

The paper makes four contributions to the environmental and energy economics literature.

Integration. It brings renewable energy, R&D, institutional quality, industrial structure, trade openness and supply-chain capability into a single coherent framework for environmental performance in advanced economies, rather than examining any one channel in isolation.

Pressure versus efficiency. It distinguishes CO_2 emissions from energy intensity and provides evidence that the green transition affects environmental pressure and environmental efficiency through different mechanisms-renewable energy operating most clearly on emissions, and R&D, income and governance operating most clearly on efficiency.

Institutions as a moderator. It identifies institutional quality as a conditioning factor that strengthens the environmental effectiveness of renewable energy and innovation. This reframes the role of governance from a direct emissions lever-where its sign is ambiguous in advanced economies-to an enabling capacity, and it offers a parsimonious resolution of the otherwise puzzling positive direct association between institutional quality and emissions in high-income panels.

Robustness and heterogeneity. It subjects the core findings to an unusually broad battery of checks-an EKC specification, institutional interactions, panel quantile estimation, a logistics-performance robustness model, and re-estimation with each of the four Worldwide Governance Indicators-thereby establishing which relationships are stable and which should be interpreted with caution.

Taken together, the results support a clear and policy-relevant message. The OECD green transition is not only a matter of installing renewable capacity and funding research; it is equally a matter of the institutional and structural conditions that determine whether those inputs are converted into lower emissions and higher energy efficiency. Governance quality, in particular, behaves as a green-transition multiplier.

Conceptual framework

Fig. 1 summarises the analytical logic that organises the paper and that the econometric models of Section 4 operationalise. The framework reads from left to right as a staged mapping from inputs to outcomes. At the left sit the green-transition *inputs*-the renewable share of energy consumption and R&D expenditure-through which advanced economies pursue decarbonisation. These inputs bear on the two environmental outcomes at the right through what we term the green-transition channel. The defining feature of the framework is the position of institutional quality. Rather than entering merely as one more determinant of emissions, institutional quality-proxied by government effectiveness, regulatory quality, the rule of law and the control of corruption-sits above the green-transition channel and *moderates* it. The vertical arrow in Fig. 1 denotes this moderating effect: the strength of the passage from green-transition inputs to environmental outcomes is itself a function of governance, so that a given expansion of renewable capacity or research effort is expected to deliver larger environmental gains where institutions are stronger. The structural controls-income, manufacturing, urbanisation and trade openness-enter the framework as contextual covariates that condition the empirical setting without being the object of the moderation hypothesis. The outcomes are deliberately divided in two. Environmental *pressure* is captured by CO_2 emissions per capita and environmental *efficiency* by energy intensity, and the framework permits the green-transition inputs, the structural controls and the institutional moderator to act on the two outcomes along distinct paths-precisely the asymmetry the empirical analysis uncovers. The right-hand node makes the policy stakes explicit: lower environmental pressure and higher environmental efficiency together constitute a more effective OECD green transition. The remainder of the paper tests each link in this framework: the direct input effects, the structural context, the nonlinearity of the income relationship and, centrally, the institutional moderation of the green-transition channel.

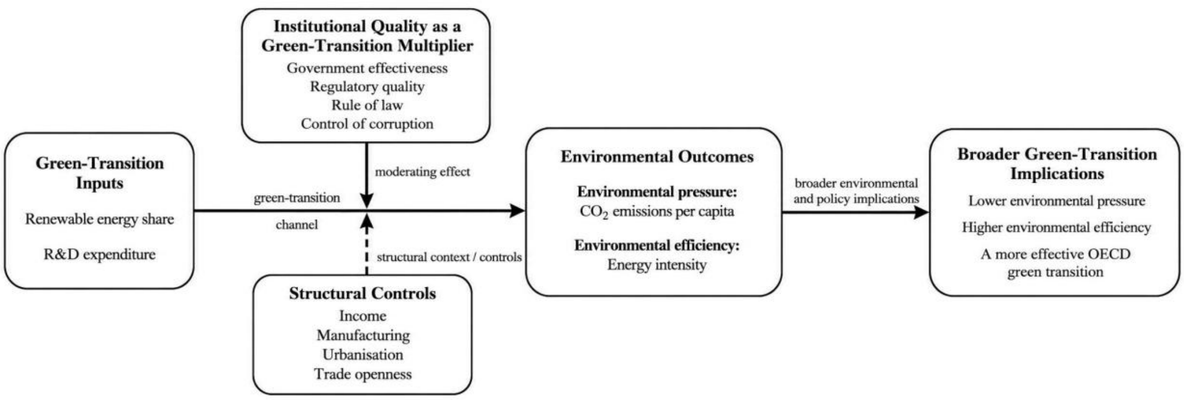

Fig. 1. Conceptual framework: green-transition inputs, institutional moderation and environmental outcomes.

Notes: Green-transition inputs (renewable energy share and R&D expenditure) act on two environmental outcomes-environmental pressure (CO_2 emissions per capita) and environmental efficiency (energy intensity)-through the green-transition channel. Institutional quality moderates this channel; structural controls condition the empirical setting. The environmental outcomes feed into the broader implications of the OECD green transition.

Structure of the paper

The remainder of the paper proceeds as follows. Section 2 reviews the relevant literature and develops six hypotheses. Section 3 describes the data, variables and sources. Section 4 sets out the econometric methodology and the sequence of models. Section 5 reports the empirical results, beginning with descriptive diagnostics and model selection and proceeding through the baseline, EKC, interaction, quantile and robustness analyses. Section 6 discusses and synthesises the findings; Section 7 draws out policy implications; Section 8 concludes; and Section 9 sets out the study's limitations and an agenda for future research.

Literature review and hypothesis development

The literature relevant to this study spans several established research programmes in environmental and energy economics. We organise the review thematically, moving from the direct drivers of emissions and efficiency to the institutional, structural and distributional considerations that motivate our framework. Within each theme we identify the prevailing evidence and the open questions that the present analysis is designed to address, and we develop testable hypotheses as we proceed.

Renewable energy and carbon emissions

Renewable energy consistently reduces carbon emissions by replacing fossil fuels in electricity, heating, and transport. Studies confirm a negative correlation between renewable energy use and CO_2 emissions, though the impact varies based on the energy system's maturity, grid flexibility, and the carbon intensity of replaced sources. Developed economies, with mature renewable technologies and ample capital, show significant and stable emission reductions.

However, whether renewable energy improves energy efficiency (energy required per unit of output) is less clear. While renewables can replace less efficient fossil processes and electrify efficient end-uses, factors like intermittency and the energy cost of infrastructure can negate or reverse short-term efficiency gains. Evidence is mixed, with some studies suggesting the efficiency benefits of renewables are weaker or more concentrated than their emissions benefits, which is why we model emissions and energy intensity separately.

Hypothesis 1. Renewable energy consumption is associated with lower CO_2 emissions per capita in OECD economies.

R&D, innovation and environmental efficiency

Green growth theory emphasizes research, development, and eco-innovation as key drivers for decoupling economic activity from environmental damage. Models suggest that policy-driven technical change promotes cleaner, energy-efficient production. Studies show R&D and green patents correlate with lower energy intensity and, eventually, reduced emissions. Efficiency gains are often seen before emission reductions, as innovation first lowers energy use per output unit. However, the environmental benefits of R&D depend on factors like domestic firm absorption, cross-sector diffusion, and supportive regulation. Without these, R&D spending may not yield efficiency improvements. In some cases, R&D can even correlate positively with emissions due to the co-location of research-intensive and energy-intensive industries, a conditionality our framework aims to address.

Hypothesis 2. R&D expenditure is associated with lower energy intensity in OECD economies, with the efficiency channel more pronounced than any direct effect on emissions.

Institutional quality, governance and environmental performance

Institutional economics posits that robust institutions—such as secure property rights, credible regulation, impartial enforcement, and corruption control—influence economic and environmental outcomes by shaping policy implementation and agent expectations (North, 1990; Acemoglu *et al.* 2001). In environmental contexts, stronger institutions are believed to enhance environmental performance by facilitating credible policy design and enforcement, diminishing incentives for environmentally damaging activities, and extending the policy horizons necessary for low-carbon investments (Ibrahim & Law 2016; Bhattacharya *et al.* 2017; Salman *et al.* 2019).

However, empirical evidence, especially in advanced economies, is mixed. While many studies link better governance to improved environmental outcomes, others show weak, insignificant, or even positive direct correlations between institutional quality and emissions in high-income nations (Lau *et al.* 2014; Abid 2017). This discrepancy is often attributed to the collinearity of institutional quality with income and the scale of energy-intensive industries. It's suggested that institutional influence on the environment is indirect, enhancing the effectiveness of other policies, rather than a direct effect. This interpretation implies that the institutional hypothesis is better tested through interactive, rather than additive, analyses, a perspective central to our study and supported by a growing body of literature on conditional institutional effects (Danish *et al.* 2019; Wang *et al.* 2021).

Hypothesis 3. Institutional quality is associated with lower energy intensity in OECD economies, while its direct association with emissions may be weak or positive and should be interpreted in conjunction with its moderating role.

Hypothesis 4. Institutional quality strengthens the environmental effectiveness of renewable energy and R&D; that is, the emission-reducing and efficiency-improving effects of these inputs are larger where governance quality is higher.

Trade openness, manufacturing and energy intensity

Trade openness impacts the environment through scale, composition, and technique effects. While it can increase emissions by expanding activity and relocating polluting industries to less regulated areas, it can also decrease emissions and energy intensity by promoting cleaner technology and boosting efficiency through competition. In advanced economies, the latter effects often dominate, leading to cleaner production. Industrial structure also plays a role; a larger manufacturing sector increases energy and carbon intensity due to its higher emissions compared to services. Urbanization has mixed effects: density can improve efficiency via shared infrastructure but also increase energy demand, with outcomes varying based on development stage and urban structure.

Hypothesis 5. Trade openness is associated with lower emissions and lower energy intensity in OECD economies, consistent with the dominance of technology-diffusion and technique effects, whereas a larger manufacturing share is associated with greater environmental pressure and energy intensity.

The Environmental Kuznets Curve and the nonlinear income–environment relationship

The Environmental Kuznets Curve (EKC) hypothesis suggests an inverted-U relationship between income and environmental degradation: initial economic growth increases pollution, but beyond a certain point, as economies develop, pollution decreases due to a shift to services, higher demand for environmental quality, and adoption of abatement technologies. However, empirical evidence for the EKC is inconsistent, varying significantly based on data, pollutants, and methodologies. For high-income economies, where CO_2 emissions may have passed their turning point, the linear income term in EKC models is often weak, with the quadratic term driving the curve. Methodologically, quadratic specifications frequently suffer from multicollinearity between income and its square, which can be largely mitigated by mean-centering.

Hypothesis 6. The income–emissions relationship in OECD economies is nonlinear, exhibiting an inverted-U tendency, whereas energy intensity declines with income approximately linearly.

Quantile and heterogeneous effects in environmental economics

Conditional-mean estimators reveal average relationships but obscure variations in outcome distribution. Quantile and method-of-moments quantile (MMQR) approaches are thus standard for environmental panels, as factors influencing emissions and energy intensity likely differ between clean/dirty or efficient/inefficient economies (Koenker & Bassett 1978; Zhu *et al.* 2016; Machado & Santos Silva 2019; Cheng *et al.* 2021). Studies consistently show that renewable energy's abatement effect and governance's influence vary across quantiles—e.g., stronger at lower emissions/energy intensity—directly impacting policy targeting. We therefore supplement our conditional-mean estimates with a panel quantile heterogeneity analysis.

Green supply chains, logistics performance and environmental efficiency

Recent literature links economic environmental performance to the efficiency of logistics and supply chains. Logistics are energy-intensive, and the quality of logistics infrastructure, measured by indices like the World Bank's LPI, impacts trade and production emissions and energy intensity (Khan *et al.* 2018; Liu *et al*. 2020). While efficient logistics can reduce energy consumption, their aggregate impact on emissions is less direct. Due to limited LPI data, we use logistics performance as a robustness check and expect its environmental influence to be primarily through energy efficiency. Our framework aligns with research presenting environmental mechanisms as staged processes. Unlike studies tracing price shocks to emissions, this paper examines how advanced economies' green-transition inputs—renewable energy, innovation, and supply-chain capability—transform into environmental pressure and efficiency, and how institutional quality mediates this conversion. Section 4 details this conceptual architecture.

Data and variables

Sample and panel structure

The analysis utilizes an annual panel of 38 OECD economies, harmonized at the country-year level, from 2000 to 2021, resulting in 746 complete observations. This restriction is due to the inconsistent reporting of governance indicators and R&D expenditure across all OECD members in recent years. By focusing on a consistent, complete-case sample, the study avoids mixing estimates from different samples and ensures all reported coefficients are derived from the same observations. The exclusion of 2022-2024 data is therefore based on data availability, not discretionary selection or environmental outcomes. The panel data is unbalanced, with annual observations per country varying from 8 to 21, averaging close to 20. This imbalance stems from differing reporting practices across countries regarding governance, innovation, and energy statistics, not from outcome-related attrition. The countries included are OECD members throughout the period, ranging from large industrial economies like the United States, Japan, and Germany to smaller, newer members (see Appendix Table A1). Two robustness samples were derived from the same data. The logistics-performance sample includes only country-year observations with an available Logistics Performance Index, resulting in 209 observations primarily from 2007–2018. Due to its sparsity, logistics performance is used solely for robustness checks. The alternative-governance sample substitutes the composite institutional-quality index with each of its four constituent indicators, using the same 746 observations as the baseline.

Dependent variables

The study uses two dependent variables that capture complementary dimensions of environmental performance. The first, CO_2 emissions per capita, measures the environmental *pressure* a society exerts and is the standard outcome in the decarbonisation literature. The second, energy intensity, measured as megajoules of energy supply per unit of GDP at 2017 purchasing-power parity, measures environmental *efficiency*-how much energy an economy requires to generate a unit of economic value. Lower values of both variables represent better environmental outcomes, but the two need not move together: an economy can lower its emissions by decarbonising its energy supply without becoming more energy-efficient, and it can improve its energy efficiency without commensurately reducing emissions if its remaining energy use stays carbon-intensive. Treating the two separately is therefore central to the paper's argument.

Explanatory variables

Our analysis uses several key variables. The "green transition" and "structural" channels are represented by renewable energy consumption (share of final energy) and R&D expenditure (gross domestic R&D as a share of GDP, indicating innovation capacity). Manufacturing value added (share of GDP) reflects industrial structure, while trade openness (the sum of exports and imports relative to GDP) captures international competition and the spread of technology. GDP per capita, in natural logarithms, measures the level of development; in the Environmental Kuznets Curve (EKC) model, its mean-centered level and squared term capture nonlinear income effects. Urbanization (urban population share) controls for settlement patterns. Institutional quality is measured by an index created from the average of four Worldwide Governance Indicators: government effectiveness, regulatory quality, rule of law, and control of corruption. Each indicator is a standardized score, with higher values indicating better governance. This composite index reduces noise and collinearity among individual indicators while retaining their common signal. For robustness, these four indicators are also examined separately to confirm the composite's validity and pinpoint which governance dimensions drive the results. The robustness analysis incorporates two additional variables: the Logistics Performance Index, intermittently observed and used to assess supply-chain capability, and four individual governance indicators. Table 1 details all variables, their definitions, units, and sources. Theoretical and prior literature suggest clear expected signs for the variables. Renewable energy should negatively impact CO_2 emissions and energy intensity. R&D expenditure is anticipated to be negative, particularly for energy intensity, due to efficiency gains from innovation. Institutional quality is hypothesized to improve both outcomes, primarily by strengthening the effects of green-transition inputs, leading to negative institution-by-input interaction terms. Among structural controls, manufacturing share is expected to positively affect both outcomes (industrial pressure). GDP per capita is projected to positively correlate with emissions (scale effect) but negatively with energy intensity (efficiency gains). In the EKC specification, a positive linear income term and negative squared term are expected if an inverted-U relationship exists. Trade openness and urbanization have ambiguous theoretical effects: openness might reduce both outcomes if technology diffusion dominates, while urbanization could increase energy use due to demand. These expectations are discussed with each result rather than imposed on the estimation.

Table 1. Variable definitions, measurement and data sources.

Variable	Definition and measurement	Role	Source
CO_2 per capita	Carbon dioxide emissions per capita (metric tonnes), AR5 basis	Dependent	WDI
Energy intensity	Energy supply per unit of GDP (MJ per 2017 PPP USD)	Dependent	WDI
Renewable energy	Renewable energy as % of final energy consumption	Core	WDI
R&D expenditure	Gross R&D expenditure as % of GDP	Core	WDI
Manufacturing	Manufacturing value added as % of GDP	Core	WDI
GDP per capita (ln)	GDP per capita, current USD, natural logarithm	Core	WDI
GDP^2(centred)	Square of mean-centred ln GDP per capita (EKC only)	Core	WDI
Urbanisation	Urban population as % of total population	Core	WDI
Trade openness	Trade (exports + imports) as % of GDP	Core	WDI
Institutional quality	Average of the four WGI scores (see below)	Core	WGI
Gov. effectiveness	Quality of public services and policy implementation	Robustness	WGI
Regulatory quality	Ability to formulate and implement sound regulation	Robustness	WGI
Rule of law	Confidence in and adherence to the rules of society	Robustness	WGI
Control of corruption	Extent to which public power is exercised for private gain (reversed)	Robustness	WGI
Logistics (LPI)	Logistics Performance Index (overall score, 1–5)	Robustness	World Bank LPI

Notes: WDI = World Bank World Development Indicators; WGI = Worldwide Governance Indicators; LPI = World Bank Logistics Performance Index. The institutional-quality index is the unweighted mean of government effectiveness, regulatory quality, rule of law and control of corruption. The baseline estimation sample is 38 OECD economies, 2000–2021, N = 746 (unbalanced). The LPI robustness sample is N = 209 (2007–2018).

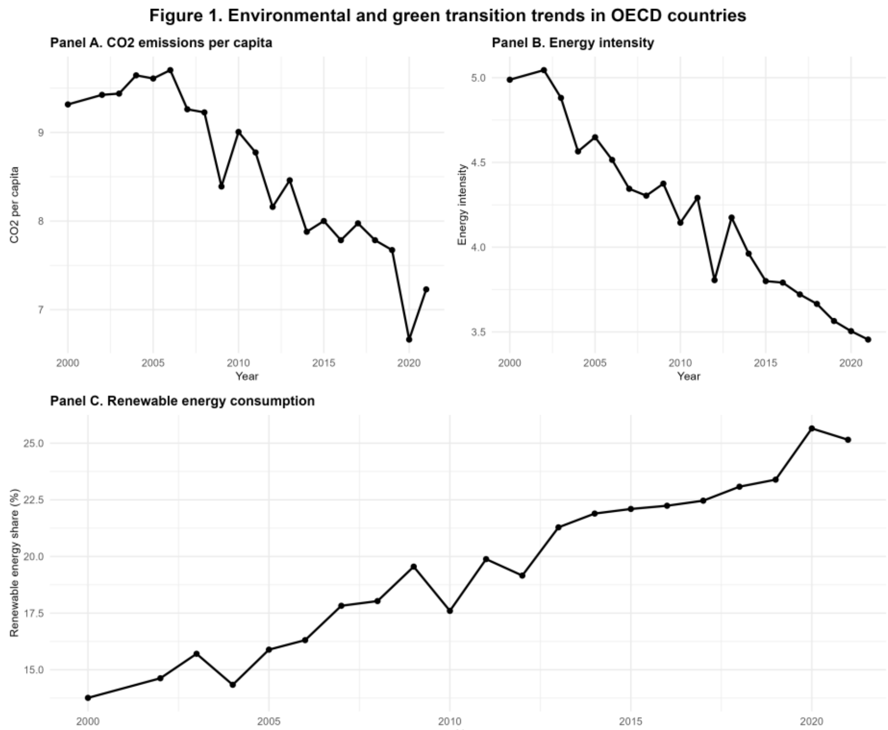

Fig. 2. Trends in environmental outcomes and renewable energy across the OECD, 2000–2021. *Notes:* OECD cross-country averages by year. Panel A: CO_2 emissions per capita (metric tons); Panel B: energy intensity (MJ per 2017 PPP USD of GDP); Panel C: renewable share of final energy consumption (%).

Trends in the data

Fig. 2 places the analysis in context by plotting the OECD averages of the two environmental outcomes and of renewable energy over the sample period. Two patterns stand out. First, both CO_2 emissions per capita (Panel A) and energy intensity (Panel B) decline over 2000–2021, indicating that the OECD has made measurable progress on both environmental pressure and environmental efficiency. Second, the renewable share of final energy consumption (Panel C) rises substantially over the same period. The co-movement is suggestive of a green transition in progress, but it is precisely the cross-country variation around these averages-and the question of what converts renewable expansion into environmental results-that the econometric analysis is designed to explain.

Methodology

This section sets out the conceptual framework, the estimation strategy and the full sequence of models. The empirical approach is designed to be transparent and progressively demanding: it begins with diagnostics and formal model selection, establishes a robust conditional-mean baseline, and then probes the baseline from four directions-nonlinearity, institutional moderation, distributional heterogeneity and alternative measurement.

Conceptual framework

The empirical models operationalise the conceptual framework set out in Figure 1. We conceive of environmental performance as the endpoint of a structured, staged process linking green-transition inputs to environmental outcomes. Three channels operate in parallel. The green-transition channel runs from clean-energy and innovation inputs-renewable energy and R&D-to environmental pressure and efficiency. The institutional channel runs from governance quality to the implementation capacity, regulatory credibility and policy transmission that determine whether green-transition inputs are realised as environmental results; crucially, this channel acts not only directly but by *moderating* the green-transition channel. The structural channel runs from the scale and composition of activity-income, industrial structure, urbanisation and trade openness-to emissions and energy intensity through production, demand and technology-diffusion effects. The three channels converge on the two outcomes, and the empirical models are organised to identify each in turn.

Why two-way fixed effects with Driscoll–Kraay standard errors

Country-level environmental panels are subject to unobserved heterogeneity on two dimensions. Time-invariant national characteristics-geography, resource endowments, energy-system legacy, deep institutional history-plausibly correlate with both the regressors and the outcomes, and omitting them biases pooled and random-effects estimates. Common temporal shocks-global energy prices, technology cost curves, the business cycle, multilateral climate agreements-affect all countries in a given year. A two-way fixed-effects (TWFE) estimator, which absorbs both country and year effects, addresses both sources of heterogeneity by identifying the parameters from within-country variation net of common time shocks. The choice is not assumed but tested: Section 5.2 reports Hausman tests that reject random effects and F-tests that reject both pooled OLS and the one-way (country-only) specification in favour of the two-way model, for both dependent variables. Inference must further accommodate the statistical pathologies typical of macro-panels: heteroskedasticity across countries, serial correlation within countries, and-most importantly-cross-sectional dependence arising from common shocks and spillovers that year dummies only partially absorb. We therefore report Driscoll–Kraay standard errors (Driscoll & Kraay, 1998), which are heteroskedasticity- and autocorrelation-consistent and, by construction, robust to general forms of cross-sectional dependence. This delivers conservative and reliable inference without imposing a parametric structure on the error dependence, and it is the appropriate standard for a panel of this dimension. The use of Driscoll–Kraay inference is motivated by the expected error structure of macro-panel environmental data, where cross-sectional dependence, serial correlation and heteroskedasticity are common. Cross-sectional dependence is assessed with the Pesaran CD test (Pesaran, 2021), serial correlation with the Wooldridge test for autocorrelation in panel models, and groupwise heteroskedasticity with a Breusch–Pagan/modified Wald test. The use of Driscoll–Kraay inference is therefore consistent with the expected error structure of macro-panel environmental data, where cross-sectional dependence, serial correlation and heteroskedasticity are common. Driscoll–Kraay standard errors provide a conservative correction for these forms of error dependence and are used throughout the two-way fixed-effects specifications. Two interpretive commitments follow from this design and are maintained throughout the paper. First, the two-way fixed-effects estimator removes all time-invariant country heterogeneity and all common annual shocks, so the slope coefficients are identified from within-country variation net of global trends. Second, and notwithstanding this, the estimates are interpreted as robust conditional associations rather than strict causal effects. The fixed-effects design does not eliminate the possibility of reverse causality or of time-varying omitted factors correlated with both the regressors and the outcomes; we are explicit about this throughout and return to it in Section 4.8.

Baseline specification

The baseline relates each environmental outcome to the green-transition, structural and institutional regressors within a two-way fixed-effects framework. For country *i* in year *t*, the general form is:

$$EP_{it} = \beta_1 REN_{it} + \beta_2 RD_{it} + \beta_3 MAN_{it} + \beta_4 lnGDP_{it} + \beta_5 URB_{it} + \beta_6 TRA_{it} + \beta_7 INST_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad \textbf{(1)}$$

where *EP* denotes environmental performance-either CO_2 emissions per capita or energy intensity; *REN* is renewable energy consumption; *RD* is R&D expenditure; *MAN* is manufacturing value added; ln*GDP* is the log of GDP per capita; *URB* is urbanisation; *TRA* is trade openness; and *INST* is the institutional-quality index. The terms μ_i and λ_t are country and year fixed effects, and ε_{it} is the idiosyncratic error. Equation (1) is estimated separately for the two outcomes, yielding the emissions equation:

$$CO2_{it} = \beta_1 REN_{it} + \beta_2 RD_{it} + \beta_3 MAN_{it} + \beta_4 lnGDP_{it} + \beta_5 URB_{it} + \beta_6 TRA_{it} + \beta_7 INST_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad \textbf{(2)}$$

and the energy-intensity equation:

$$ENI_{it} = \beta_1 REN_{it} + \beta_2 RD_{it} + \beta_3 MAN_{it} + \beta_4 lnGDP_{it} + \beta_5 URB_{it} + \beta_6 TRA_{it} + \beta_7 INST_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad \textbf{(3)}$$

where *ENI* denotes energy intensity. All slope coefficients are interpreted as within-country associations, conditional on common annual shocks.

Environmental Kuznets Curve specification

To test the nonlinear income–environment relationship, we augment the baseline with a quadratic income term. Because the level and square of income are mechanically collinear, we first mean-centre log GDP per capita and then square the centred variable, which greatly reduces the correlation between the linear and quadratic terms without altering the implied curvature. The emissions EKC equation is:

$$CO2_{it} = \beta_1 REN_{it} + \beta_2 RD_{it} + \beta_3 MAN_{it} + \beta_4 lnGDP^{c}{}_{it} + \beta_5 (lnGDP^{c}{}_{it})^2 + \beta_6 URB_{it} + \beta_7 TRA_{it} + \beta_8 INST_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad \textbf{(4)}$$

where $lnGDP^{c}$ is mean-centred log GDP per capita. An inverted-U (EKC) pattern requires $\beta_4 > 0$ and $\beta_5 < 0$ with both significant; the implied turning point in log income is $-\beta_4 / (2\beta_5)$, which is then re-expressed in income levels by adding back the sample mean and exponentiating. The same specification is estimated for energy intensity to test whether the efficiency–income relationship is similarly curved or, as we hypothesise, approximately linear.

Institutional interaction models

The core test of the moderation hypothesis introduces interactions between institutional quality and each green-transition input. To render the constituent terms interpretable and to limit collinearity, the input and the institutional index are mean-centred before forming the product. For input $X \in renewableenergy, R\&D$, the interaction model is:

$$EP_{it} = \beta_1 X_{it}{}^{c} + \beta_2 INST_{it}{}^{c} + \beta_3 (X_{it}{}^{c} \times INST_{it}{}^{c}) + \gamma' Z_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad \textbf{(5)}$$

where X^{c} and $INST^{c}$ are the mean-centred input and institutional index, Z is the vector of remaining controls, and β_3 is the coefficient of interest. A negative and significant β_3 indicates that higher institutional quality strengthens the emission-reducing (or efficiency-improving) effect of the input-the moderation predicted by Hypothesis 4. Four such models are estimated: renewable energy and R&D, each interacted with institutional quality, for each of the two outcomes.

Panel quantile heterogeneity analysis

To examine whether the relationships vary across the conditional distribution of the outcomes, we estimate a panel quantile specification with country and year fixed effects. For quantile τ, the conditional quantile function is: $Q\tau(EP_{it}|X_{it}) = \alpha_i(\tau) + \lambda_t(\tau) + \beta(\tau)' X_{it} + \varepsilon_{it}(\tau)$ **(6)**

where X is the full vector of explanatory variables, $\alpha_i(\tau)$ and $\lambda_t(\tau)$ are country and year effects estimated at quantile τ, and the coefficient vector $\beta(\tau)$ is permitted to vary across quantiles $\tau \in (0.10, 0.25, 0.50, 0.75, 0.90)$.

We refer to this as a panel quantile fixed-effects estimation. It delivers the distributional information that motivates the conditional-quantile literature-how the effect of each covariate changes across the conditional distribution of the outcome-and complements, rather than substitutes for, the conditional-mean fixed-effects baseline. We adopt the cautious label "panel quantile heterogeneity analysis" in preference to a strong method-of-moments (MMQR) claim, in the spirit of the quantile-via-moments approach of Machado and Santos Silva (2019) but without asserting that the full MMQR estimator is implemented. The analysis identifies whether, for instance, the abatement effect of renewable energy or the efficiency effect of institutions is stronger among cleaner or more energy-intensive economies.

Robustness specifications

Logistics performance

To assess the supply-chain-capability channel, we add the Logistics Performance Index to the baseline on the reduced LPI sample:

$$EP_{\mathrm{it}} = \beta_1 LPI_{\mathrm{it}} + \beta_2 REN_{\mathrm{it}} + \beta_3 RD_{\mathrm{it}} + \gamma' Z_{\mathrm{it}} + \mu_{\mathrm{i}} + \lambda_{\mathrm{t}} + \varepsilon_{\mathrm{it}} \qquad \textbf{(7)}$$

Since the LPI is observed only intermittently (N = 209, 2007–2018), this specification is interpreted with caution and is reported for robustness only; it is estimated under both one-way and two-way fixed effects, the latter with Driscoll–Kraay errors.

Alternative governance indicators

To verify that the institutional findings are not an artefact of the composite index, we replace *INST* with each of the four Worldwide Governance Indicators in turn-government effectiveness, regulatory quality, the rule of law and the control of corruption-re-estimating Equations 2 and 3 for each. This both confirms the robustness of the other coefficients and reveals which dimensions of governance carry the institutional effect.

Identification, endogeneity and dynamic GMM

The interpretation of the estimates as conditional associations reflects a deliberate and conservative stance on identification. Three of the focal regressors-renewable energy, R&D and institutional quality-are plausibly endogenous. Reverse causality is conceivable: cleaner or more energy-efficient economies may, for political-economy reasons, invest more in renewables and research, and environmental performance may itself shape the demand for stronger governance. Time-varying omitted factors-shifts in environmental preferences, unobserved technology shocks, or contemporaneous policy bundles-could also correlate with both the regressors and the outcomes. The two-way fixed-effects design absorbs all time-invariant national characteristics and all common annual shocks, which removes the most important sources of confounding, but it does not by itself deliver exogeneity. We therefore refrain from causal language and report associations that are robust across estimators and across the conditional distribution. Dynamic panel estimation by the generalised method of moments (GMM) was considered as a means of addressing persistence and endogeneity. In this moderate-N, unbalanced panel, however, difference- and system-GMM specifications failed to deliver stable coefficients and credible diagnostics-instrument proliferation and weak-instrument problems were severe, and the post-estimation tests were not reliable. Reporting unstable GMM estimates would convey false precision, so GMM results are not retained as evidence; the issue is revisited in the limitations (Section 9). The two-way fixed-effects framework with Driscoll–Kraay inference, supported by the formal model-selection tests, is therefore adopted as the estimation backbone, and the robustness of its conclusions is established through the EKC, interaction, quantile and alternative-measurement analyses rather than through a single dynamic specification.

Empirical results

This section presents the results in the sequence anticipated by the methodology. We begin with descriptive diagnostics and the formal model-selection tests, which jointly justify the two-way fixed-effects baseline. We then report the baseline estimates for both outcomes, the EKC results, the institutional interactions, the distributional analysis and, finally, the two robustness families. To keep the main text focused, the most consequential tables and figures are reported here; full diagnostic, quantile and robustness output is collected in the Appendix.

Descriptive statistics, correlation and multicollinearity

Table 2 summarises the estimation sample. The dispersion is substantial and economically meaningful. Per-capita CO_2 emissions average 8.5 tonnes but range from 1.3 to 26.0, and energy intensity averages 4.2 MJ per PPP dollar with a long right tail (skewness 2.5), reflecting the coexistence of highly efficient service economies and more energy-intensive members. The renewable share averages roughly 20% but spans from under 1% to over 80%, capturing the wide variation in green-transition progress that the analysis seeks to explain. Income, governance and innovation also vary widely, providing the within- and between-country variation on which identification rests. The Pearson correlation matrix (Appendix Table A2; visualised in Appendix Fig. A1) shows that pairwise correlations among the regressors are generally moderate. The only correlation exceeding the 0.70 screening threshold is that between institutional quality and log GDP per capita (0.81), which is expected-governance quality and income co-evolve-and which foreshadows the interpretive care required for the direct institutional coefficient in the emissions equation. Crucially, the variance-inflation factors confirm that multicollinearity is not a threat to estimation: every VIF is below 5 (Appendix Table A3), with the highest, for log GDP per capita, at 3.9 in the baseline and 4.3 in the centred EKC specification. Mean-centring keeps the VIFs of the linear and quadratic income terms comfortably within acceptable bounds.

Table 2. Descriptive statistics (baseline sample, N = 746).

Variable	Mean	SD	Median	Min	Max	Skew.
CO_2 per capita	8.53	4.37	8.14	1.30	26.04	1.02
Energy intensity	4.16	1.90	3.70	1.09	15.65	2.54
Renewable energy (%)	19.61	15.94	15.20	0.70	82.90	1.45
R&D (% GDP)	1.77	1.05	1.61	0.13	5.83	0.61
Manufacturing (% GDP)	14.83	5.07	14.18	4.55	34.89	0.66
GDP per capita (ln)	10.19	0.77	10.33	7.75	11.81	-0.56
Urbanisation (%)	75.87	10.65	77.48	49.76	94.63	-0.39
Trade openness (% GDP)	95.10	56.72	76.96	19.56	397.51	2.02
Institutional quality	1.15	0.65	1.22	-0.60	2.21	-0.44

Notes: Energy intensity is in MJ per 2017 PPP USD. Institutional quality is the average of the four standardised WGI scores. Statistics are computed on the 746-observation baseline sample.

Model selection tests

Before interpreting any coefficients, we establish the appropriate estimator through formal testing. Table 3 reports the model-selection battery. For both dependent variables the Hausman test decisively rejects the random-effects specification (χ^2 = 58.9 for emissions and 622.7 for energy intensity, both $p < 0.01$), indicating that the country effects are correlated with the regressors and that a fixed-effects estimator is required. The F-test for individual effects rejects pooled OLS in favour of country fixed effects (F = 252.9 and 295.6, both $p < 0.01$), confirming the presence of substantial unobserved national heterogeneity. Finally, the F-test for time effects rejects the one-way (country-only) model in favour of the two-way specification (F = 4.3 and 7.9, both $p < 0.01$), establishing that common annual shocks are also relevant. The tests therefore point unambiguously to the two-way fixed-effects model, which-combined with Driscoll–Kraay standard errors-constitutes the baseline.

Table 3. Model-selection tests.

Test (null hypothesis)	Outcome	Statistic	p-value	Decision
Hausman: RE consistent	CO_2	58.89	<0.01	Reject → FE
Hausman: RE consistent	Energy int.	622.67	<0.01	Reject → FE
F: pooled OLS adequate	CO_2	252.94	<0.01	Reject → FE
F: pooled OLS adequate	Energy int.	295.57	<0.01	Reject → FE
F: time effects not needed	CO_2	4.25	<0.01	Reject → TWFE
F: time effects not needed	Energy int.	7.89	<0.01	Reject → TWFE

Notes: Hausman statistics are $\chi^2(7)$; F-statistics are for individual effects (FE vs pooled) and twoway effects (TWFE vs FE). TWFE = two-way fixed effects. Full panel-model comparisons appear in Appendix Table A4.

Baseline two-way fixed-effects estimates

Table 4 reports the baseline estimates for both outcomes. The two columns tell visibly different stories, and that contrast is the empirical heart of the paper: the green transition reaches environmental *pressure* and environmental *efficiency* through different channels. Figure 3 displays the same coefficients with 95% confidence intervals.

Carbon emissions per capita

Renewable energy is the standout result for emissions: its coefficient is −0.116 and highly significant ($p < 0.01$), confirming Hypothesis 1. Within countries and net of common shocks, a higher renewable share is robustly associated with lower per-capita CO_2 emissions, as the substitution of clean for fossil generation would predict.

Trade openness also carries a negative and significant coefficient (−0.023, $p < 0.01$), consistent with the view that, for technologically advanced economies, openness diffuses cleaner technology and disciplines producers rather than displacing pollution-support for the emissions component of Hypothesis 5.

Table 4. Baseline two-way fixed-effects estimates with Driscoll–Kraay standard errors.

Regressor	CO_2 per capita	Energy intensity
Renewable energy	-0.1161*** (0.0257)	0.0034 (0.0108)
R&D expenditure	0.4206*** (0.1466)	-0.2450*** (0.0866)
Manufacturing	0.1935*** (0.0214)	0.0580*** (0.0185)
GDP per capita (ln)	1.3908*** (0.4289)	-0.9691*** (0.1305)
Urbanisation	0.0167** (0.0070)	0.0281*** (0.0093)
Trade openness	-0.0233*** (0.0048)	-0.0103*** (0.0028)
Institutional quality	0.8890*** (0.2253)	-0.4553*** (0.0848)
Country FE	Yes	Yes
Year FE	Yes	Yes
Observations	746	746
Within R^2	0.351	0.267

Notes: Driscoll–Kraay standard errors (maxlag = 2) in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Within R^2 refers to the two-way within transformation. The same coefficients are plotted in Fig. 3.

The remaining variables are positively associated with emissions. Manufacturing (0.194, $p < 0.01$) and log GDP per capita (1.391, $p < 0.01$) raise emissions through the scale and composition of activity, and urbanisation enters positively but with a small coefficient (0.017, $p < 0.05$). R&D carries a positive direct coefficient (0.421, $p < 0.01$), and institutional quality is likewise positive and significant (0.889, $p < 0.01$). These last two associations require careful interpretation and should not be read as evidence that innovation or good governance increase pollution. Both R&D and institutional quality are strongly correlated with advanced, high-income industrial structures-institutional quality and income correlate at 0.81 in this sample-so their positive direct coefficients in part capture the emissions associated with the kind of economy in which research capacity and strong governance are found. As Sections 5.5 and 5.6 show, the environmentally important role of institutions is interactive and efficiency-related rather than directly emissions-reducing, and reading the direct coefficient in isolation would be misleading.

Energy intensity

The energy-intensity column reveals the channels that the emissions column obscures. Four variables reduce energy intensity significantly: R&D expenditure (−0.245, $p < 0.01$), log GDP per capita (−0.969, $p < 0.01$), trade openness (−0.010, $p < 0.01$) and institutional quality (−0.455, $p < 0.01$). The R&D result confirms Hypothesis 2-innovation's environmental contribution surfaces most clearly as improved efficiency rather than as a direct cut in emissions. The income result indicates that richer OECD economies use energy more efficiently, consistent with structural shifts towards services and the adoption of efficient technology. The negative trade coefficient again supports the technology-diffusion interpretation, and the negative institutional coefficient provides direct support for Hypothesis 3: better governance is associated with more efficient energy use even where it is not associated with lower emissions. By contrast, manufacturing (0.058, $p < 0.01$) and urbanisation (0.028, $p < 0.01$) raise energy intensity, as the structural hypothesis predicts. Renewable energy is not significant in the energy-intensity baseline (0.003, $p = 0.75$), an asymmetry with its strong emissions effect that vindicates the decision to model the two outcomes separately: renewable deployment decarbonises the energy supply without necessarily reducing the quantity of energy required per unit of output. As Section 5.6 shows, however, renewable energy does reduce energy intensity once distributional heterogeneity is allowed for, indicating that its mean effect masks meaningful variation across the distribution.

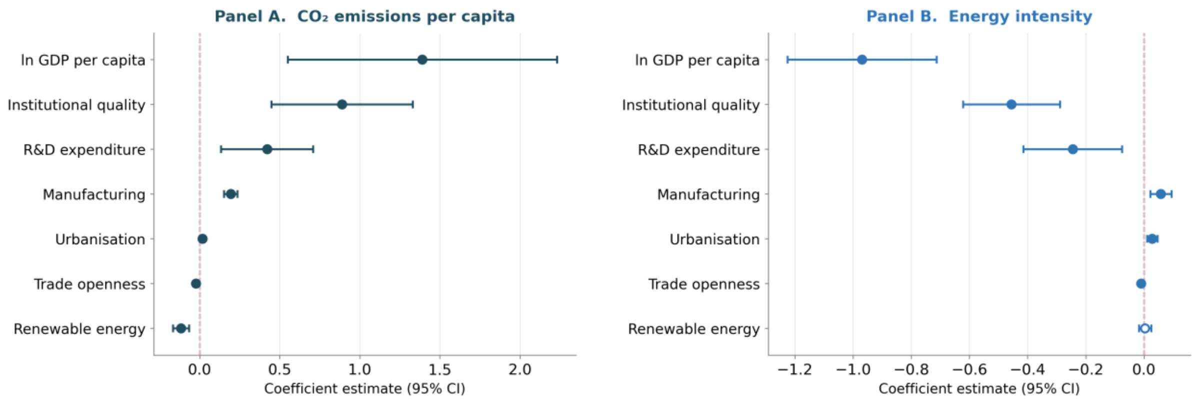

Fig. 3. Baseline coefficients for CO_2 emissions (left) and energy intensity (right), two-way fixed effects with Driscoll–Kraay 95% confidence intervals.

Fig. 3. makes the asymmetry visible at a glance. For emissions (left), renewable energy and trade openness sit clearly to the left of zero, while income, institutional quality, R&D and manufacturing lie to the right. For energy intensity (right), income, institutional quality, R&D and trade openness fall to the left of zero, while manufacturing and urbanisation fall to the right, and renewable energy straddles zero. The variables that reduce emissions are not the same as those that reduce energy intensity-precisely the pattern that motivates an integrated, two-outcome framework.

Environmental Kuznets Curve results

Table 5 presents the Environmental Kuznets Curve (EKC) and interaction results. Regarding income terms for emissions, the significant negative squared-income term (−0.606, $p < 0.01$) and a non-significant positive linear term (0.275, $p = 0.50$) suggest a nonlinear, inverted-U relationship, rather than a fully confirmed EKC. While curvature is present and statistically robust, the imprecise linear term prevents claiming a canonical EKC. The estimated turning point of approximately USD 33,300 GDP per capita is economically plausible within the OECD income range, supporting Hypothesis 6 by suggesting many OECD members have passed the point where income growth increases emissions. For energy intensity, the pattern differs. A strong negative linear-income term (−1.011, $p < 0.01$) and an insignificant squared term (−0.023, $p = 0.70$) indicate an approximately linear decline in energy intensity with income, rather than an inverted U. This monotone relationship shows richer OECD economies are more energy-efficient, without the rise-then-fall pattern seen in emissions. This contrast highlights that pressure and efficiency respond to income via different functional forms, further supporting Hypothesis 6.

Institutional interaction results

Panel B of Table 5 reports the central finding of the paper, and Fig. 4 displays it. All four institution-by-input interaction coefficients are negative and statistically significant. For emissions, the renewable-by-institution interaction is −0.113 ($p < 0.01$) and the R&D-by-institution interaction is −0.447 ($p < 0.01$). For energy intensity, the corresponding interactions are −0.022 ($p < 0.05$) and −0.264 ($p < 0.05$). The uniformity of the result is striking: irrespective of the input (renewable energy or R&D) or the outcome (emissions or energy intensity), higher institutional quality strengthens the environmental effectiveness of the green-transition input. This is direct and consistent support for Hypothesis 4. This interpretation resolves the apparent paradox of a positive direct correlation between institutional quality and emissions in advanced economies. Institutions don't inherently reduce emissions; their positive direct coefficient reflects their association with high-income industrial structures. Instead, institutions amplify the effectiveness of policy interventions. In environments with robust governance, investments in renewable energy or research more effectively lead to reduced emissions and increased efficiency. This is because strong institutions provide the necessary implementation capacity, regulatory credibility, coordination, monitoring, and policy transmission for such initiatives. Therefore, institutional quality acts as a "green-transition multiplier" rather than a direct emissions-reduction tool. This reframing, from institutions as a direct lever to institutions as an enabling condition, is the study's primary conceptual contribution.

Table 5. Environmental Kuznets Curve and institutional interaction results (key terms).

Term	CO_2 per capita	Energy intensity
Panel A. EKC specification (Eq. 4)		
ln GDP per capita (centred)	0.2748 (0.4067)	-1.0105*** (0.2058)
ln GDP per capita $(centred)^2$	-0.6062*** (0.1976)	-0.0225 (0.0589)
Renewable energy	-0.1123*** (0.0222)	0.0036 (0.0105)
Institutional quality	0.5823*** (0.1964)	-0.4667*** (0.0703)
Implied turning point (USD)	≈ 33,300	n.a. (linear)
Panel B. Institutional interaction terms (Eq. 5)		
Renewable × Institutional quality	-0.1133*** (0.0102)	-0.0222** (0.0099)
R&D × Institutional quality	-0.4471*** (0.1054)	-0.2640** (0.1139)

Notes: Driscoll–Kraay standard errors in parentheses. *** p < 0.01, ** *p* < 0.05, * *p* < 0.10. Panel A reports the key terms of the EKC specification (Eq. 4); income is mean-centred before squaring. Panel B reports the interaction coefficients from four separate models (Eq. 5), each containing the centred input, the centred institutional index and the full control set. Full output appears in Appendix Tables A5 and A6.

The moderating effect is clearest when viewed as a marginal effect. With mean-centered inputs and institutional index, the marginal effect of renewable energy on CO_2 emissions is calculated as its centered coefficient plus the interaction coefficient multiplied by institutional quality: -0.081 + (-0.113) × institutional quality (centered). At the sample mean of institutional quality, the marginal effect is approximately -0.081, becoming more negative by about 0.113 for each unit increase in institutional quality. This indicates that renewable energy provides significantly greater abatement in OECD economies with stronger governance. Similarly, the marginal effect of R&D on emissions, +0.472 + (-0.447) × institutional quality, shifts from positive with low governance to zero or negative as institutional quality improves, implying that innovation's emissions effect is activated by institutional capacity. This principle also applies to energy intensity, where stronger institutions enhance efficiency gains from both inputs. A marginal-effects plot illustrating these slopes at varying institutional quality levels, with confidence bands derived from the coefficient covariance matrix, would directly visualize this mechanism and is recommended. Fig. 4 confirms that all interaction estimates, with their confidence intervals, are less than zero. Both emissions and energy-intensity interactions show consistent directional effects. The greater R&D-by-institution effects suggest that governance significantly influences innovation, likely because research absorption and diffusion depend more heavily on institutional capacity than renewable energy integration.

Panel quantile heterogeneity

While conditional-mean estimates show the average relationship, environmental performance determinants can vary significantly among economies. Table 6 presents key variable panel quantile results, with full estimates in Appendix Table A7 and Appendix Figs. A2–A3. For CO_2 emissions, renewable energy consistently reduces emissions across all quantiles, indicating a widespread abatement effect. This effect is more pronounced in cleaner economies (10^{th} percentile: -0.146) and less so in emissions-intensive ones (90^{th} percentile: -0.108), suggesting that renewable energy yields greater abatement in cleaner economies where structural and infrastructural factors may not impede its impact as much. Income and manufacturing increase emissions across the distribution, while institutional quality consistently shows a positive correlation, aligning with baseline findings and interaction evidence rather than a direct effect. Distributional analysis of energy intensity reveals that renewable energy, initially appearing insignificant, actually improves energy efficiency across most of the conditional distribution. This suggests the previously observed null mean effect was due to offsetting variations, not a lack of relationship. Income and trade openness consistently reduce energy intensity, supporting their role in efficiency. Institutional quality most effectively reduces energy intensity in lower and middle quantiles, with diminishing returns at higher quantiles, becoming insignificant at the 90^{th} percentile. This distributional evidence reinforces the central conclusions.

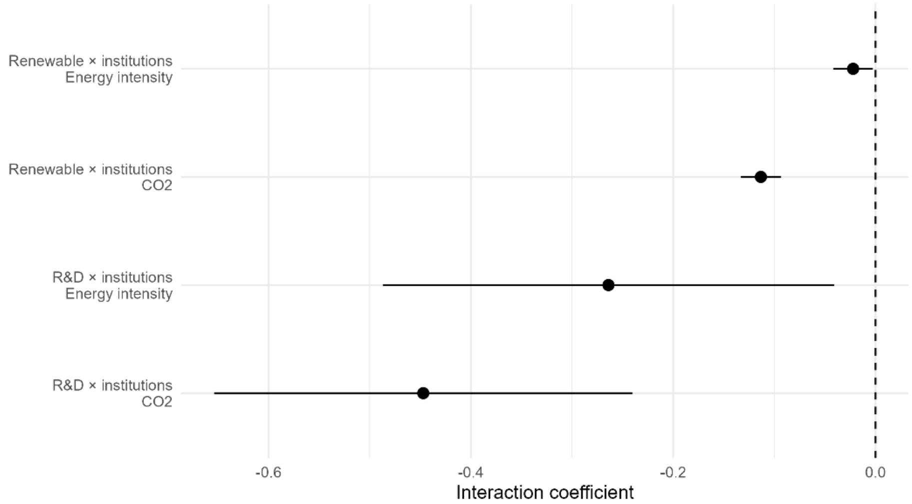

Fig. 4. Institutional quality as a moderating channel: the four institution-by-input interaction coefficients with 95% confidence intervals. All four lie entirely below zero.

Robustness checks

This section consolidates the robustness evidence, elaborating on the stability of income and distributional results previously established by the EKC specification (Section 5.4) and panel quantile analysis (Section 5.6). We present two additional checks—logistics performance and alternative governance indicators—to clarify which conclusions are robust and which require cautious interpretation.

Logistics performance

Panel B of Table 6 presents a logistics-performance check, with estimates considered indicative due to the small and sparse LPI sample (N = 209, primarily 2007–2018). While logistics performance is not robustly linked to CO_2 emissions, it shows a significant negative association with energy intensity (−0.104, $p < 0.05$ for two-way FE; −0.315, $p < 0.05$ for country FE). This aligns with supply-chain literature and our predictions in Section 2.7: modern logistics reduce energy consumption in goods movement, enhancing energy efficiency without necessarily causing an immediate, detectable drop in overall emissions, as logistics is only one part of the energy system. This suggests that logistics and supply-chain capabilities primarily impact efficiency rather than overall pressure. Given the limited sample, this serves as supporting evidence rather than a primary conclusion.

Alternative governance indicators

Panel C re-estimates the model using individual Worldwide Governance Indicators (WGI) instead of the composite index, clarifying previous findings. For energy intensity, all four indicators—government effectiveness (-0.332), regulatory quality (-0.241), rule of law (-0.308), and control of corruption (-0.252)—show highly significant negative coefficients ($p < 0.01$), confirming that institutional efficiency consistently impacts energy intensity across all governance dimensions. Regarding emissions, direct effects vary: government effectiveness, rule of law, and control of corruption are positive and significant, while regulatory quality is not. These direct emission effects are not over-interpreted, as they reflect income-governance collinearity, reinforcing that institutions primarily enhance efficiency and green-transition effectiveness rather than directly reducing emissions. Key findings regarding renewable energy, income, manufacturing, and trade openness remain consistent across all four models (Appendix Table A8), demonstrating robustness regardless of the governance measure.

Summary of robustness

Across all analyses, three consistent findings emerge: renewable energy reduces CO_2 emissions; improved institutional quality decreases energy intensity and enhances green initiatives; and income, manufacturing, and trade openness consistently show their expected effects. Two findings require cautious interpretation: the logistics-performance result, due to a small sample size, and the direct positive link between institutional quality and emissions, which likely reflects collinearity with income rather than a direct behavioral impact. The Environmental Kuznets Curve for emissions is better described as an inverted-U trend than a definite curve.

Table 6. Robustness and heterogeneity summary.

Variable / model	CO_2 **per capita**	**Energy intensity**
Panel A. Panel quantile estimates (sign and significance across τ)		
Renewable energy	− at all τ (stronger at low **τ**)	− at 4 of 5 τ
GDP per capita (ln)	+ at all **τ**	− at all τ
Institutional quality	+ at all **τ**	− at low/mid τ
Trade openness	− at all **τ**	− at all τ
Panel B. Logistics Performance Index (Eq. 7; N = 209)		
LPI (two-way FE + DK)	0.1262 (0.2126)	-0.1042** (0.0430)
LPI (country FE)	-0.2968 (0.3803)	-0.3147** (0.1264)
Panel C. Alternative WGI indicators (direct effect; two-way FE + DK)		
Government effectiveness	1.0076*** (0.1544)	-0.3317*** (0.0686)
Regulatory quality	0.1749 (0.3460)	-0.2406*** (0.0800)
Rule of law	0.6703*** (0.2333)	-0.3080*** (0.0877)
Control of corruption	0.3714** (0.1563)	-0.2517*** (0.0638)

Notes: Panel A summarises the sign and significance of the quantile estimates across $\tau \in (0.10, 0.25, 0.50, 0.75, 0.90)$ (full estimates in Appendix Table A7). Panels B and C report point estimates with Driscoll–Kraay (DK) or clustered standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Each WGI row is the indicator's coefficient from a separate model in which it replaces the composite index.

DISCUSSION

The findings in Section 5 reveal distinct, channel-specific environmental mechanisms, rather than a single relationship. Two key aspects organize this discussion:

1. Separation of Environmental Pressure and Efficiency: CO_2 emissions per capita (pressure) and energy intensity (efficiency) respond differently to various covariates. A variable beneficial for one aspect might be neutral or detrimental to the other.
2. Pervasive Institutional Interaction Effects: All estimated interactions are negative and significant, suggesting governance plays a moderating, rather than direct, role.

These two points inform our interpretation of the results and link them to the study's input-to-outcome logic.

The green-transition channel: renewable energy and innovation

The study's most robust finding is that renewable energy consistently lowers CO2 emissions. This association holds true across various models, including those accounting for income and different points of the conditional emissions distribution. The impact is more pronounced in economies with lower initial carbon intensity but remains significant even in high-emission contexts. This consistent evidence suggests a structural relationship between renewable energy deployment and reduced emissions within the OECD. Innovation, especially in R&D, doesn't immediately lower emissions; in fact, it might even increase them in economically dynamic regions. Its true environmental impact lies in boosting efficiency, leading to reduced energy intensity. This suggests that innovation in advanced economies primarily contributes to environmental improvement by optimizing energy use per unit of output, rather than directly cutting overall emissions. This nuance is crucial for studies assuming innovation directly reduces emissions, as its benefits are initially seen in energy efficiency and only later, indirectly, in overall emissions.

Institutions as a green-transition multiplier

The study's most counter-intuitive findings concern institutional quality. Resolving these is central to the study's contribution. The direct coefficient for institutional quality is positive in the emissions equation and negative in the energy-intensity equation. A superficial interpretation of the former suggests that improved governance increases emissions, which is unlikely. However, two factors mitigate this interpretation: firstly, institutional quality correlates strongly with per capita income in the OECD panel ($r \approx 0.81$), making it difficult to separate the direct emissions coefficient from economic activity scale. This suggests a partial association due to collinearity rather than a behavioral impact of governance on emissions. Secondly, and more importantly, the interaction terms provide a coherent explanation that the direct terms alone cannot. Strong institutions amplify the environmental benefits of renewable energy and R&D. Specifically, improvements in regulatory quality, rule of law, government effectiveness, and corruption control enhance the emissions and energy intensity reductions achieved through increased renewable capacity or research. Thus, institutions act as a "green-transition multiplier," determining the effectiveness with which clean energy and innovation lead to environmental gains, rather than directly reducing emissions themselves. This moderating role of institutional capacity is consistent across all individual governance indicators.

Economic development, industrial structure and the two faces of environmental performance

Per capita income demonstrates a dual relationship with emissions and energy intensity, as predicted by the pressure-efficiency framework. Higher incomes correlate with increased emissions but decreased energy intensity, a trend observed across various income levels. This suggests that advanced economies become more energy-efficient with development, even as their economic growth drives up overall emissions. While not a definitive Environmental Kuznets Curve, an inverted-U trend for emissions is observed, with a potential turning point within the sample's income range. However, the insignificant linear term prevents strong conclusions. Conversely, energy intensity shows a consistently linear, downward-sloping relationship, indicating continuous improvement with development without a reversal. This distinction highlights that while related, emissions and efficiency are governed by different dynamics. Industrial structure has an inverse effect on both economic margins. A higher manufacturing share correlates with increased emissions and energy intensity across all quantiles, indicating manufacturing unequivocally drives environmental strain in OECD nations by boosting both emissions and energy consumption per output unit. This is a structural, not technological, outcome, highlighting that industrial transformation, alongside energy supply decarbonization, is crucial for environmental performance.

Trade, logistics and the diffusion of cleaner production

Increased trade openness correlates with reduced emissions and energy intensity. This suggests that for developed nations, trade allows access to cleaner imported technologies, exposes producers to international efficiency standards, and promotes best practices. There is no evidence of a "pollution haven" within the OECD; rather, openness appears environmentally beneficial. Logistics performance, while not directly linked to emissions, significantly reduces energy intensity. Efficient supply chains decrease the energy needed for goods movement, improving overall efficiency. This supports the idea that supply chain improvements primarily impact energy efficiency, a finding consistent with broader observations that green-transition initiatives often first enhance energy efficiency. This conclusion is made with caution due to the limited logistics data.

A staged reading: from green-transition inputs to environmental outcomes

Our analysis models the green transition as a staged system, building on Sindarov *et al.* (2026). The initial stage involves green-transition inputs: renewable energy deployment and innovation. An intermediate stage comprises conditioning factors—institutional capacity, trade openness, and logistics—that influence the efficiency of input absorption and transmission. The final stage presents two environmental outcomes: emissions and energy intensity. This framework clarifies why renewables directly impact emissions, while innovation and logistics primarily affect efficiency. Institutions enhance the transmission from inputs to outcomes, and development and industrial structure exert opposing effects on the two outcomes. Thus, an advanced economy's environmental performance stems not from a single policy but from its institutions' ability to convert clean energy and innovation into reduced emissions and increased efficiency.

Policy implications

The channel-specific structure of the evidence carries direct implications for the design of OECD green-transition policy. The central lesson is that no single instrument acts on every margin of environmental performance: emissions and energy efficiency respond to different levers, and the return to each lever depends on the institutional setting in which it is deployed. Six implications follow, stated as policy directions that the evidence supports rather than as prescriptions for any particular country.

Treat renewable-energy expansion as the primary emissions instrument. Renewable deployment is the most robust emissions-reducing lever in the analysis, with a negative association that holds across estimators and across the entire conditional distribution of emissions. Because the effect is proportionally larger in lower-emission settings, sustained support for renewables is warranted both in economies already advancing decarbonisation and at the high-emission tail, where the marginal effect, though smaller, remains material.

Pair green innovation policy with institutional capacity. R&D is associated with improved energy efficiency rather than with immediate emissions reductions, and its environmental payoff is amplified where governance is strong. Innovation support-research funding, technology deployment, demonstration programmes-should therefore be designed as an efficiency strategy and embedded in a capable regulatory and administrative framework, since the same research effort yields larger environmental returns where institutions function well.

Target energy-efficiency policy at industry and the urban fabric. A larger manufacturing share is associated with both higher emissions and higher energy intensity, and urbanisation adds further pressure. This identifies industrial transformation and the energy performance of cities-not energy-supply decarbonisation alone-as decisive margins. Efficiency standards, industrial-process upgrading and urban energy planning address pressure at its structural source.

Sustain trade openness while reinforcing environmental standards. Within the OECD, openness is associated with lower emissions and lower energy intensity, consistent with the diffusion of cleaner technologies and exposure to international efficiency standards. The evidence gives no support to protective measures justified on environmental grounds; openness is better paired with robust standards so that the technology-and-technique benefits of trade are fully realised.

Recognise logistics modernisation as efficiency policy. Logistics performance is associated with lower energy intensity but not with measurable changes in aggregate emissions. Investment in efficient freight, transport and supply-chain infrastructure should accordingly be valued for its contribution to the energy efficiency of the economy, and counted within the efficiency rather than the headline-emissions component of a green-transition strategy.

Invest in institutional quality as a green-transition multiplier. Because every interaction between governance and the green-transition inputs is environmentally favourable, strengthening regulatory quality, the rule of law, government effectiveness and the control of corruption raises the environmental return on every other instrument. Institutional capacity is best understood not as an alternative to renewables, innovation or efficiency policy but as the condition under which those policies deliver their full effect.

CONCLUSION

This study examined how the green transition shapes environmental performance across thirty-eight OECD economies over the period 2000–2021, distinguishing throughout between environmental pressure, measured by carbon emissions per capita, and environmental efficiency, measured by energy intensity. Using a two-way fixed-effects framework with Driscoll–Kraay standard errors and an extensive set of robustness procedures-an Environmental Kuznets Curve specification, institutional interaction terms, panel quantile estimation, a logistics-performance check and re-estimation across alternative governance indicators-it set out to identify the channels through which renewable energy, innovation and institutions affect environmental outcomes in advanced economies. The evidence points to a green transition that operates as a structured system rather than through a single lever. Renewable energy emerges as the clearest and most durable emissions-reducing force, its effect holding across every part of the conditional distribution. Innovation and supply-chain capability act primarily on the efficiency margin, lowering the energy a given level of activity requires rather than depressing emissions immediately. Economic development reduces energy intensity even as the scale of activity continues to raise emissions, and a larger manufacturing base intensifies pressure on both margins, identifying industrial structure as a distinct front for environmental policy. Trade openness, within this group of advanced economies, is associated with both cleaner and more efficient production. The study's central contribution is its account of institutions. Governance does not reliably push emissions down on its own-indeed, its direct association with emissions is positive and entangled with income in high-income economies-but it consistently magnifies the environmental effectiveness of renewable energy and innovation, an amplifying role that proved robust across every dimension of governance examined. The decisive environmental function of institutions in advanced economies is therefore to govern the transmission from green-transition inputs to environmental outcomes. What ultimately determines the environmental performance of an OECD economy is less any single instrument than the institutional capacity to translate clean-energy and innovation effort into realised gains in both emissions and efficiency. Building that capacity, alongside the continued expansion of renewables and the structural transformation of energy-intensive activity, is the surest foundation for a credible green transition.

Limitations and future research

Several limitations qualify these findings and define a constructive agenda for further work. The panel is unbalanced, with country coverage varying from eight to twenty-one annual observations; although the fixed-effects framework with Driscoll–Kraay standard errors is well suited to such data and to the cross-sectional dependence and serial correlation it exhibits, the uneven coverage means that some countries contribute more heavily than others to the estimated relationships. The logistics-performance analysis is more tightly constrained still: The Logistics Performance Index is available only intermittently, yielding a small and sparse sub-sample, so the logistics results-though consistent with theory-are best regarded as indicative and warrant confirmation as longer series accumulate. The data are annual, which suits the study of structural environmental relationships but cannot capture higher-frequency dynamics such as the short-run response of emissions to energy-price movements or to abrupt shifts in policy. The analysis is also associational. The fixed-effects design absorbs all time-invariant country heterogeneity and common time shocks, and the consistency of the core results across estimators and across the conditional distribution lends them credibility; nonetheless, the possibility of residual endogeneity-through reverse causality or time-varying omitted factors-means the estimates should be read as robust conditional associations rather than as identified causal effects. In this connection we note that a dynamic system-GMM estimator was explored during the analysis but did not yield stable or well-identified results in this panel and was therefore not retained; we report this transparently rather than presenting fragile dynamic estimates. These limitations suggest clear extensions. Higher-frequency-quarterly or monthly-data would permit explicit modelling of short-run environmental dynamics and of the transmission of energy-price and policy shocks. Firm- or sector-level indicators of green supply-chain activity would sharpen the logistics and structural channels well beyond what an aggregate logistics index allows. Incorporating explicit measures of environmental policy stringency and carbon pricing would help separate the institutional-capacity channel emphasised here from the direct effect of specific policy instruments. Finally, research designs built around credible sources of exogenous variation-policy discontinuities, staggered reforms or instrumental strategies-would move the institutional-moderation result from robust association toward causal identification. Pursuing these directions would deepen, and usefully test, the staged input-to-outcome account of the OECD green transition developed in this paper.

REFERENCES

Abass, RAR *et al.* 2025, Reimagining research for renewable energy resources solutions: Integrating Intergovernmental Panel on Climate Change assessments for effective global action. *Unconventional Resources* 6: 100165.

Abid, M 2017, Does economic, financial and institutional developments matter for environmental quality? A comparative analysis of EU and MEA countries. *Journal of Environmental Management*, 188: 183–194.

Abrorov, S 2019, The importance of sukuk in the development of economy: as an example of its impact on the income of the malaysian population. *Journal of Advanced Research in Dynamical and Control Systems*, 11(7): 927-931.

Acemoglu, D, Aghion, P, Bursztyn, L & Hemous, D 2012, The environment and directed technical change. *American Economic Review*, 102(1): 131–166.

Acemoglu, D, Johnson, S & Robinson, JA 2001, The colonial origins of comparative development: An empirical investigation. *American Economic Review*, 91(5): 1369–1401.

Adams, S & Acheampong, AO 2019, Reducing carbon emissions: The role of renewable energy and democracy. *Journal of Cleaner Production*, 240: 118245.

Aghion, P, Dechezleprêtre, A, Hémous, D, Martin, R & Van Reenen, J 2016, Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry. *Journal of Political Economy,* 124(1): 1–51.

Algburi, Sameer *et al.* "Environmental impact assessment of carbon-negative bio-based plastics advancing sustainable feedstock utilization." *Bioresource Technology Reports* 30 (2025): 102124.

Ali, Bashar Mahmood *et al.* "Sustainable strategies for preventive maintenance and replacement in photovoltaic power systems: Enhancing reliability, efficiency, and system economy." *Unconventional Resources* 6 (2025): 100170.

Ang, JB 2007, CO_2 emissions, energy consumption, and output in France. *Energy Policy*, 35(10): 4772–4778.

Antweiler, W, Copeland, BR & Taylor, MS 2001, Is free trade good for the environment? *American Economic Review*, 91(4): 877–908.

Apergis, N & Payne, JE 2010, Renewable energy consumption and economic growth: Evidence from a panel of OECD countries. *Energy Policy*, 38(1): 656–660.

Arellano, M & Bond, S 1991, Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. *Review of Economic Studies*, 58(2): 277–297.

Baltagi, BH 2021, *Econometric Analysis of Panel Data*. 6th edn, Springer, Cham.

Bekun, FV, Alola, AA & Sarkodie, SA 2019, Toward a sustainable environment: Nexus between CO_2 emissions, resource rent, renewable and nonrenewable energy in 16-EU countries. *Science of the Total Environment*, 657: 1023–1029.

Bhattacharya, M, Churchill, SA & Paramati, SR 2017, The dynamic impact of renewable energy and institutions on economic output and CO_2 emissions across regions. *Renewable Energy*, 111: 157–167.

Bilgili, F, Koçak, E & Bulut, Ü 2016, The dynamic impact of renewable energy consumption on CO_2 emissions: A revisited Environmental Kuznets Curve approach. *Renewable and Sustainable Energy Reviews*, 54: 838–845.

Blundell, R & Bond, S 1998, Initial conditions and moment restrictions in dynamic panel data models. *Journal of Econometrics*, 87(1): 115–143.

Cheng, C, Ren, X, Dong, K, Dong, X & Wang, Z 2021, How does technological innovation mitigate CO_2 emissions in OECD countries? Heterogeneous analysis using panel quantile regression. *Journal of Environmental Management*, 280: 111818.

Cole, MA 2007, Corruption, income and the environment: An empirical analysis. *Ecological Economics*, 62(3–4): 637–647.

Copeland, BR & Taylor, MS 2004, Trade, growth, and the environment. *Journal of Economic Literature*, 42(1): 7–71.

Danish, Ulucak, R & Khan, SU-D 2019, Determinants of the ecological footprint: Role of renewable energy, natural resources, and urbanization. *Sustainable Cities and Society*, 54: 101996.

Dinda, S 2004, Environmental Kuznets Curve hypothesis: A survey. *Ecological Economics*, 49(4): 431–455.

Dogan, E & Seker, F 2016, Determinants of CO_2 emissions in the European Union: The role of renewable and non-renewable energy. *Renewable Energy*, 94: 429–439.

Driscoll, JC & Kraay, AC 1998, Consistent covariance matrix estimation with spatially dependent panel data. *Review of Economics and Statistics*, 80(4): 549–560.

Fernández Fernández, Y, Fernández López, MA & Olmedillas Blanco, B 2018, Innovation for sustainability: The impact of R&D spending on CO_2 emissions. *Journal of Cleaner Production*, 172: 3459–3467.

Frankel, JA & Rose, AK 2005, Is trade good or bad for the environment? Sorting out the causality. *Review of Economics and Statistics*, 87(1): 85–91.

Gozgor, G, Lau, CKM & Lu, Z 2018, Energy consumption and economic growth: New evidence from the OECD countries. *Energy*, 153: 27–34.

Grossman, GM & Krueger, AB 1991, Environmental impacts of a North American Free Trade Agreement. *NBER Working Paper*, no. 3914, National Bureau of Economic Research, Cambridge, MA.

Grossman, GM & Krueger, AB 1995, Economic growth and the environment. *Quarterly Journal of Economics*, 110(2): 353–377.

Hausman, JA 1978, Specification tests in econometrics. *Econometrica*, 46(6): 1251–1271.

Hoechle, D 2007, Robust standard errors for panel regressions with cross-sectional dependence. *Stata Journal*, 7(3): 281–312.

Ibrahim, MH & Law, SH 2016, Institutional quality and CO_2 emission–trade relations: Evidence from sub-Saharan Africa. *South African Journal of Economics*, 84(2): 323–340.

Im, KS, Pesaran, MH & Shin, Y 2003, Testing for unit roots in heterogeneous panels. *Journal of Econometrics*, 115(1): 53–74.

Indhumathi, R *et al.* 2025, Hybrid quantum–cloud framework for nonlinear clustering optimization and intelligent resource management. *Results in Nonlinear Analysis* 8(3): 26-35.

Jaffe, AB, Newell, RG & Stavins, RN 2005, A tale of two market failures: Technology and environmental policy. *Ecological Economics*, 54(2–3): 164–174.

Khan, MK, Teng, J-Z & Khan, MI 2018, Effect of energy consumption and economic growth on carbon dioxide emissions in Pakistan with dynamic ARDL simulations approach. *Environmental Science and Pollution Research*, 26: 23480–23490.

Koenker, R & Bassett, G 1978, Regression quantiles. *Econometrica*, 46(1): 33–50.

Lau, L-S, Choong, C-K & Eng, Y-K 2014, Investigation of the Environmental Kuznets Curve for carbon emissions in Malaysia: Do foreign direct investment and trade matter? *Energy Policy*, 68: 490–497.

Liu, X, Latif, K, Latif, Z & Li, N 2020, The interactions between renewable energy consumption, economic growth, and CO_2 emissions: Evidence from panel data. *Environmental Science and Pollution Research*, 27: 38492–38503.

Machado, JAF & Santos Silva, JMC 2019, Quantiles via moments. *Journal of Econometrics*, 213(1): 145–173.

Mahmood, H, Maalel, N & Zarrad, O 2019, Trade openness and CO_2 emissions: Evidence from Tunisia. *Sustainability*, 11(12): 3295.

Managi, S, Hibiki, A & Tsurumi, T 2009, Does trade openness improve environmental quality? *Journal of Environmental Economics and Management*, 58(3): 346–363.

Menyah, K & Wolde-Rufael, Y 2010, CO_2 emissions, nuclear energy, renewable energy and economic growth in the US. *Energy Policy*, 38(6): 2911–2915.

Mensah, CN, Long, X, Boamah, KB, Bediako, IA, Dauda, L & Salman, M 2018, The effect of innovation on CO_2 emissions of OECD countries from 1990 to 2014. *Environmental Science and Pollution Research*, 25: 29678–29698.

Mudhee, KH *et al.* 2025, Assessing climate strategies of major energy corporations and examining projections in relation to Paris Agreement objectives within the framework of sustainable energy. *Unconventional Resources*, 5: 100127.

North, DC 1990, *Institutions, Institutional Change and Economic Performance*. Cambridge University Press, Cambridge.

Pesaran, MH 2007, A simple panel unit root test in the presence of cross-section dependence. *Journal of Applied Econometrics*, 22(2): 265–312.

Pesaran, MH 2021, General diagnostic tests for cross-sectional dependence in panels. *Empirical Economics*, 60: 13–50.

Petrović, P & Lobanov, MM 2020, The impact of R&D expenditures on CO_2 emissions: Evidence from sixteen OECD countries. *Journal of Cleaner Production*, 248: 119187.

Popp, D 2002, Induced innovation and energy prices. *American Economic Review*, 92(1): 160–180.

Porter, ME & van der Linde, C 1995, Toward a new conception of the environment–competitiveness relationship. *Journal of Economic Perspectives*, 9(4): 97–118.

Roodman, D 2009, How to do xtabond2: An introduction to difference and system GMM in Stata. *Stata Journal*, 9(1): 86–136.

Sadorsky, P 2009, Renewable energy consumption and income in emerging economies. *Energy Policy*, 37(10): 4021–4028.

Sadorsky, P 2013, Do urbanization and industrialization affect energy intensity in developing countries? *Energy Economics*, 37: 52–59.

Sadorsky, P 2014, The effect of urbanization on CO_2 emissions in emerging economies. *Energy Economics*, 41: 147–153.

Salman, M, Long, X, Dauda, L & Mensah, CN 2019, The impact of institutional quality on economic growth and carbon emissions: Evidence from Indonesia, South Korea and Thailand. *Journal of Cleaner Production*, 241: 118331.

Shahbaz, M, Nasir, MA & Roubaud, D 2017, Environmental degradation in France: The effects of FDI, financial development, and energy innovations. *Energy Economics*, 74: 843–857.

Sharif, A, Raza, SA, Ozturk, I & Afshan, S 2019, The dynamic relationship of renewable and nonrenewable energy consumption with carbon emission: A global study with the application of heterogeneous panel estimations. *Renewable Energy*, 133: 685–691.

Sindarov *et al.* 2026, Energy price shocks, fossil fuel dependence, and carbon emissions (CO_2): A multi-stage transmission framework analysis. *(Forthcoming).*

Soytas, U & Sari, R 2009, Energy consumption, economic growth, and carbon emissions: Challenges faced by an EU candidate member. *Ecological Economics*, 68(6): 1667–1675.
Stern, DI 2004, The rise and fall of the Environmental Kuznets Curve. *World Development*, 32(8): 1419–1439.
Stern, DI 2017, The environmental Kuznets curve after 25 years. *Journal of Bioeconomics*, 19: 7–28.
Wang, Z, Bui, Q, Zhang, B & Pham, TLH 2021, Biomass energy production and its impacts on the ecological footprint: An investigation of the G7 countries. *Science of the Total Environment*, 743: 140741.
Westerlund, J 2007, Testing for error correction in panel data. *Oxford Bulletin of Economics and Statistics*, 69(6): 709–748.
Zhu, H, Duan, L, Guo, Y & Yu, K 2016, The effects of FDI, economic growth and energy consumption on carbon emissions in ASEAN-5: Evidence from panel quantile regression. *Economic Modelling*, 58: 237–248.

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Appendix

Table A1. OECD member economies included in the estimation sample.

Thirty-eight OECD economies (unbalanced panel, 2000–2021; N = 746)			
Australia	Austria	Belgium	Canada
Chile	Colombia	Costa Rica	Czechia
Denmark	Estonia	Finland	France
Germany	Greece	Hungary	Iceland
Ireland	Israel	Italy	Japan
Korea, Rep.	Latvia	Lithuania	Luxembourg
Mexico	Netherlands	New Zealand	Norway
Poland	Portugal	Slovak Republic	Slovenia
Spain	Sweden	Switzerland	Türkiye
United Kingdom	United States		

Notes: Country coverage is unbalanced, ranging from 8 to 21 annual observations per country (mean ≈ 19.6). Classification follows OECD membership.

Table A2. Pairwise correlation matrix of model variables.

Variable	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1. CO_2 per capita	1								
2. Energy intensity	.404	1							
3. Renewable energy	-.254	.328	1						
4. R&D intensity	.330	.148	-.006	1					
5. Manufacturing	-.106	.016	-.299	.110	1				
6. ln GDP per capita	.499	.026	.083	.620	-.263	1			
7. Urbanisation	.252	.122	.056	.442	-.390	.442	1		
8. Trade openness	.245	-.092	-.090	-.122	.057	.221	-.151	1	
9. Institutional quality	.515	.181	.192	.581	-.252	**.811**	.402	.165	1

Notes: Lower triangle reported. Column numbers correspond to the row labels. The only pairwise coefficient at or above 0.80 in absolute value (shown in colour) is that between institutional quality and ln GDP per capita (0.811), which informs the interpretation of the direct institutional coefficients in the emissions equation; all remaining correlations are moderate.

Table A3. Variance inflation factors, baseline specification.

Variable	**VIF**	**Assessment**
ln GDP per capita	3.88	Acceptable
Institutional quality	3.23	Acceptable
R&D intensity	2.66	Acceptable
Manufacturing share	1.75	Acceptable
Urbanisation	1.69	Acceptable
Trade openness	1.33	Acceptable
Renewable energy	1.17	Acceptable

Notes: All variance inflation factors are well below the conventional threshold of 5, indicating no problematic multicollinearity. Under the centred Kuznets specification all factors likewise remain below 5 (maximum 4.34 on centred ln GDP per capita).

Table A4. Model fit across panel estimators.

Dependent variable	Estimator	N	R²	Adj. R²
CO_2 per capita	Pooled OLS	746	0.421	0.415
	Random effects	746	0.526	0.522
	Country fixed effects	746	0.550	0.522
	Two-way fixed effects	746	**0.351**	0.290
Energy intensity	Pooled OLS	746	0.193	0.186
	Random effects	746	0.534	0.530
	Country fixed effects	746	0.573	0.546
	Two-way fixed effects	746	**0.267**	0.198

Notes: The two-way fixed-effects specification (the reported baseline) absorbs both country and year effects; its within R^2 is mechanically lower than the country-only fixed-effects R^2 because year effects remove additional common variation. Hausman tests reject random effects for both outcomes (CO_2: $\chi^2 = 58.9$; energy intensity: $\chi^2 = 622.7$; both $p < 0.01$), and F-tests confirm the joint significance of the time effects ($p < 0.01$).

Table A5. Environmental Kuznets Curve specification, full coefficient set.

Variable	CO_2 per capita	Energy intensity
ln GDP per capita (centred)	0.2748 (0.4067)	-1.0105*** (0.2058)
ln GDP per capita (centred)²	-0.6062*** (0.1976)	-0.0225 (0.0589)
Renewable energy	-0.1123*** (0.0222)	0.0036 (0.0105)
R&D intensity	0.3881*** (0.1398)	-0.2462*** (0.0860)
Manufacturing share	0.1970*** (0.0200)	0.0582*** (0.0181)
Urbanisation	-0.0011 (0.0090)	0.0275*** (0.0104)
Trade openness	-0.0235*** (0.0042)	-0.0103*** (0.0028)
Institutional quality	0.5823*** (0.1964)	-0.4667*** (0.0703)
Implied turning point (USD)	≈ 33,300	n.a. (linear)

Notes: Two-way fixed effects with Driscoll–Kraay standard errors (in parentheses). Income is mean-centred so that the linear term is evaluated at the sample mean. For CO_2 the negative quadratic with an insignificant linear term indicates an inverted-U tendency rather than a fully confirmed Kuznets curve; for energy intensity the relationship is essentially linear. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table A6. Institutional interaction specifications, full coefficient set.

Variable	Renewable × Inst.	R&D × Inst.
Panel A. Dependent variable: CO_2 per capita		
Renewable energy	-0.0812*** (0.0169)	-0.1193*** (0.0261)
R&D intensity	0.2787 (0.1706)	0.4724*** (0.1548)
Institutional quality	0.7361*** (0.2169)	0.8055*** (0.2056)
Renewable × Institutional quality	-0.1133*** (0.0102)	-

Variable	Renewable × Inst.	R&D × Inst.
R&D × Institutional quality	-	-0.4471*** (0.1054)
Manufacturing share	0.1648*** (0.0196)	0.1943*** (0.0208)
ln GDP per capita	1.4081*** (0.3557)	1.2112*** (0.4191)
Urbanisation	0.0518*** (0.0091)	0.0123 (0.0078)
Trade openness	-0.0246*** (0.0051)	-0.0241*** (0.0048)
Panel B. Dependent variable: energy intensity		
Renewable energy	0.0102 (0.0108)	0.0016 (0.0111)
R&D intensity	-0.2727*** (0.0861)	-0.2144*** (0.0789)
Institutional quality	-0.4852*** (0.0877)	-0.5046*** (0.0924)
Renewable × Institutional quality	-0.0222** (0.0099)	-
R&D × Institutional quality	-	-0.2640** (0.1139)
Manufacturing share	0.0524*** (0.0161)	0.0585*** (0.0179)
ln GDP per capita	-0.9657*** (0.1195)	-1.0751*** (0.1136)
Urbanisation	0.0350*** (0.0091)	0.0256*** (0.0093)
Trade openness	-0.0106*** (0.0028)	-0.0109*** (0.0028)

Notes: Two-way fixed effects with Driscoll–Kraay standard errors (in parentheses). In each interaction model the two focal variables are mean-centred prior to forming the product term, so their coefficients are evaluated at sample means. The four interaction terms (in bold) are uniformly negative, indicating that institutional quality amplifies the environmental effectiveness of both renewable energy and R&D. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table A7. Panel quantile regression estimates across the conditional distribution.

Variable	τ = 0.10	τ = 0.25	τ = 0.50	τ = 0.75	τ = 0.90
Panel A. Dependent variable: CO_2 per capita					
Renewable energy	-0.146*** (0.009)	-0.142*** (0.007)	-0.133*** (0.013)	-0.116*** (0.006)	-0.108*** (0.009)
R&D intensity	0.100 (0.061)	-0.043 (0.103)	0.290* (0.153)	0.169** (0.076)	0.285*** (0.093)
Manufacturing	0.125*** (0.014)	0.121*** (0.020)	0.178*** (0.034)	0.229*** (0.022)	0.190*** (0.018)
ln GDP per capita	0.777*** (0.157)	0.599*** (0.138)	1.422*** (0.238)	1.657*** (0.140)	1.452*** (0.140)
Urbanisation	0.018** (0.007)	0.014 (0.012)	0.016 (0.013)	0.023** (0.010)	0.021** (0.010)
Trade openness	-0.009*** (0.002)	-0.006* (0.003)	-0.011** (0.005)	-0.012*** (0.002)	-0.009*** (0.003)
Institutional quality	0.421** (0.172)	0.581*** (0.147)	0.659*** (0.228)	0.746*** (0.146)	0.747*** (0.147)
Panel B. Dependent variable: energy intensity					
Renewable energy	-0.008* (0.004)	-0.013*** (0.004)	-0.013*** (0.003)	-0.013*** (0.004)	-0.011*** (0.004)

Variable	τ = 0.10	τ = 0.25	τ = 0.50	τ = 0.75	τ = 0.90
R&D intensity	-0.070** (0.035)	-0.103*** (0.028)	-0.059** (0.029)	-0.038 (0.029)	-0.035 (0.029)
Manufacturing	0.007 (0.008)	0.005 (0.003)	0.023*** (0.005)	0.012* (0.007)	0.013** (0.006)
ln GDP per capita	-0.600*** (0.057)	-0.551*** (0.056)	-0.679*** (0.086)	-0.763*** (0.068)	-0.707*** (0.062)
Urbanisation	0.026*** (0.004)	0.020*** (0.003)	0.020*** (0.003)	0.014** (0.007)	0.021*** (0.008)
Trade openness	-0.004*** (0.001)	-0.004*** (0.001)	-0.005*** (0.001)	-0.003*** (0.001)	-0.004*** (0.001)
Institutional quality	-0.510*** (0.076)	-0.568*** (0.065)	-0.380*** (0.083)	-0.154** (0.074)	-0.068 (0.079)

Notes: Panel quantile (fixed-effects) estimates (standard errors in parentheses). The renewable-energy effect on CO_2 is negative at every quantile and proportionally larger at lower quantiles; the institutional effect on energy intensity is negative across most of the distribution but attenuates toward the upper tail. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table A8. Alternative governance indicators and logistics-performance robustness.

Governance / robustness measure	CO_2 per capita	Energy intensity
Panel A. Individual Worldwide Governance Indicators		
Government effectiveness	1.0076*** (0.1544)	-0.3317*** (0.0686)
Regulatory quality	0.1749 (0.3460)	-0.2406*** (0.0800)
Rule of law	0.6703*** (0.2333)	-0.3080*** (0.0877)
Control of corruption	0.3714** (0.1563)	-0.2517*** (0.0638)
Panel B. Logistics Performance Index (N = 209)		
Logistics performance (two-way FE + DK)	0.1262 (0.2126)	-0.1042** (0.0430)
Logistics performance (country FE)	-0.2968 (0.3803)	-0.3147** (0.1264)

Notes: Each row in Panel A is a separate two-way fixed-effects model in which the composite institutional index is replaced by the individual governance indicator shown; Driscoll–Kraay standard errors are in parentheses. Panel B reports the logistics-performance robustness check on the smaller LPI sample. The two-way fixed-effects LPI model uses Driscoll–Kraay standard errors, while the country fixed-effects specification is reported as an additional reduced-sample robustness check. Logistics performance is not robustly associated with CO_2 emissions but is negatively and significantly associated with energy intensity. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

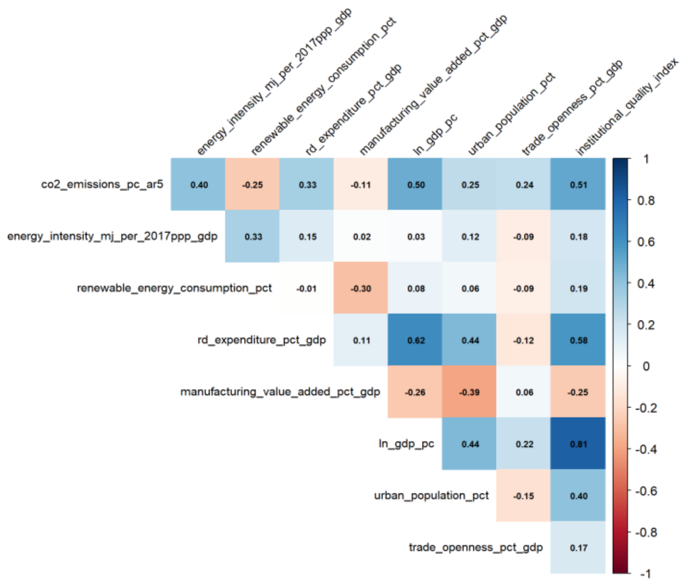

Fig. A1. Correlation heat map of model variables. *Notes:* Warmer cells denote stronger positive correlations and cooler cells stronger negative correlations. The strongest association is between institutional quality and ln GDP per capita.

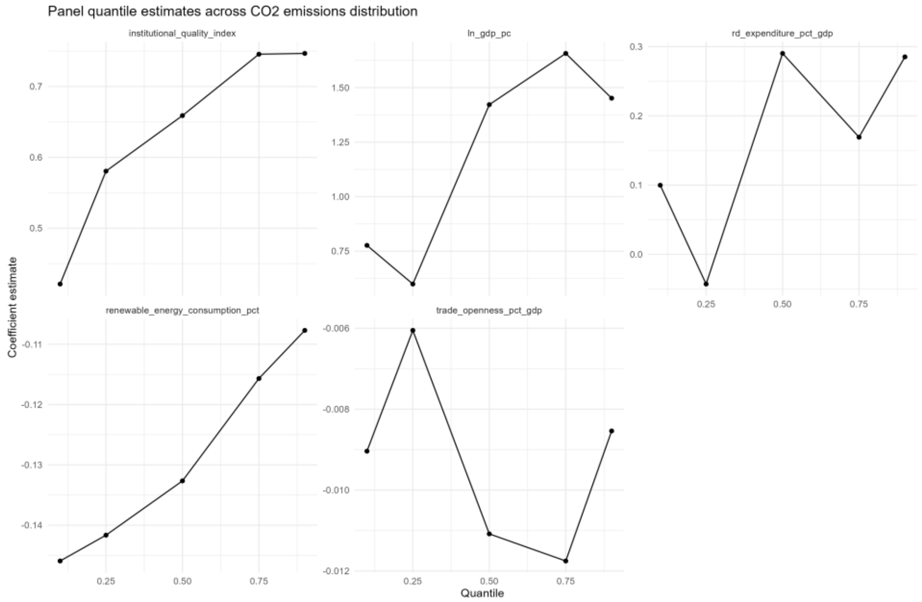

Fig. A2. Quantile coefficient paths - CO_2 emissions per capita. *Notes:* Estimated coefficients (vertical axis) plotted across conditional quantiles of CO_2 emissions (horizontal axis), with shaded confidence bands.

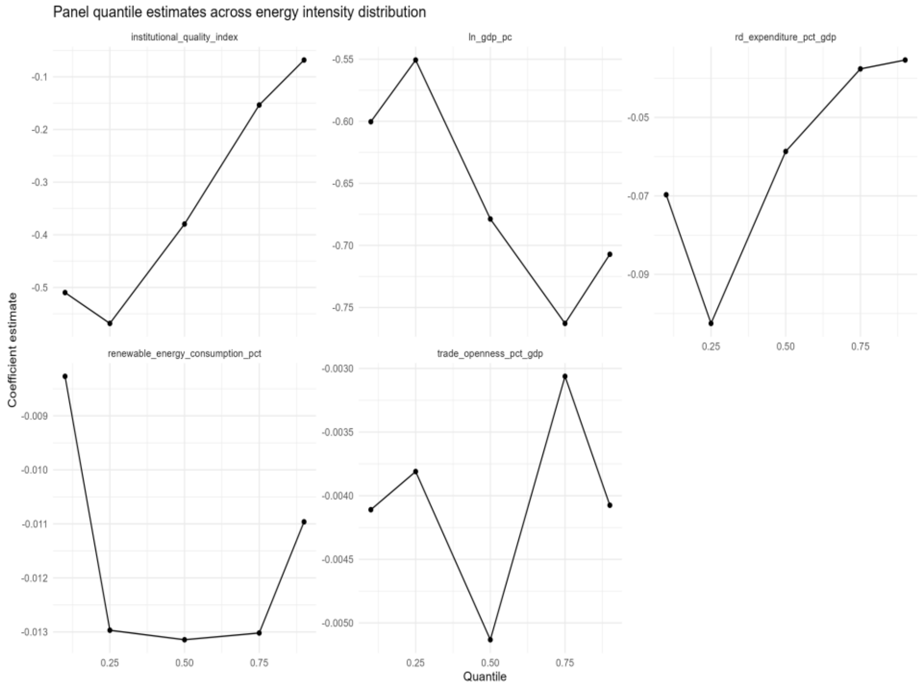

Fig. A3. Quantile coefficient paths - energy intensity. *Notes:* Estimated coefficients (vertical axis) plotted across conditional quantiles of energy intensity (horizontal axis), with shaded confidence bands.