“Transport sustainability governance and green growth in the EU-27: Evidence from panel CS-ARDL and MMQR models”

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TRANSPORT SUSTAINABILITY GOVERNANCE AND GREEN GROWTH IN THE EU-27: EVIDENCE FROM PANEL CS-ARDL AND MMQR MODELS

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Abstract

The study examines the nexus between environmental tax revenues, renewable energy adoption, transport research and development expenditure, and green growth across EU-27 countries from 2000 to 2024. The study addresses the critical gap in understanding how fiscal environmental instruments and technological innovation in transport sectors contribute to sustainable development outcomes. Using panel data analysis, the paper employs cross-sectionally augmented autoregressive distributed lag (CS-ARDL) and method of moments quantile regression (MMQR) models to analyze both short-run and long-run relationships while accounting for cross-sectional dependence and heterogeneity. Results reveal that environmental tax revenues positively influence green growth with a long-run elasticity of 0.358, indicating that a 1% increase in environmental taxes enhances adjusted net savings by 0.358%. Renewable energy adoption demonstrates a stronger positive effect with an elasticity of 0.531 in the long run, while transport R&D expenditure exhibits a coefficient of 0.289, suggesting significant contributions to sustainable outcomes. The MMQR analysis demonstrates heterogeneous effects across quantiles, with stronger impacts observed at higher green growth levels. Cross-sectional dependency tests confirm significant spatial spillover effects among EU member states. The findings provide empirical evidence supporting the effectiveness of coordinated environmental fiscal policies and targeted innovation investments in transport sectors.

Keywords adjusted net savings, fiscal environmental instruments, panel cointegration, cross-sectional dependence, quantile heterogeneity, low-carbon transition, double dividend

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INTRODUCTION

The EU's environmental governance agenda centers on transport's 2050 carbon-neutrality target under the European Green Deal. Despite decarbonization in energy and industry, transport still accounts for 25% of EU greenhouse gas emissions (European Environment Agency, 2024). While power generation has increased renewable penetration, transport emissions have only decreased moderately over the past two decades, revealing a fundamental disconnect between the sector's growth trajectory and EU climate objectives. Transport is crucial to economic competitiveness and social cohesion; therefore, reducing mobility without viable alternatives risks exacerbating geographical and distributional imbalances within and between member states. The policy issue is to reduce emissions while preserving and improving long-term welfare, which green growth, operationalized through adjusted net savings inclusive of environmental harm, aims to achieve. Thus, European sustainability governance must, both theoretically and in practice, determine which fiscal and innovation instruments best transform transport-sector action into measurable green growth gains.

Three EU policies stand out for decarbonizing transport and supporting green growth. First, environmental taxes on energy, motor vehicles, and pollutants internalize externalities and fund green investment. The "double dividend" hypothesis claims that such taxes promote environmental quality and economic efficiency, but institutional capacity and revenue recycling arrangements vary widely throughout the EU-27, determining whether these dividends materialize. Second, successive Renewable Energy Directives require renewable energy to be used for final consumption, thereby reducing the carbon intensity of the electricity that powers electrified transport. Biomass and hydrogen pathways offer additional pathways for hard-to-electrify modes. However, renewable integration varies widely among member states, and long-run panel evaluations have not assessed its contribution to adjusted net savings at the EU-27 level. Third, governmental and private support for transport R&D creates electric drivetrains, sophisticated traffic management, and alternative fuels needed to decouple mobility from pollution. Despite their policy relevance, the long-term effects of these three channels on green growth, and the extent to which they vary across countries at different sustainability performance levels, remain underexplored.

1. LITERATURE REVIEW

Research on the correlation between green growth, represented by adjusted net savings (% GNI), and environmental tax revenues (% GDP) typically reveals a positive yet context-sensitive influence, wherein taxes facilitate sustainability by internalizing externalities and financing green initiatives, although outcomes differ by region and policy framework. Abdullah and Morley (2014) examined EU and OECD nations from 1995 to 2006 through panel Granger non-causality tests employing cointegration and error correction models. The findings indicated long-term causality from adjusted net savings and GDP to environmental taxes, while reverse causality was minimal, implying that sustainable growth facilitates increased tax revenues without significantly hindering growth. The OECD (2015) conducted a descriptive study of OECD and partner economies from 2011 to 2015, observing that environmental taxes redistribute burdens to foster green growth, which correlates with increased adjusted net savings via subsidy reductions; however, without providing precise coefficients. Batrancea et al. (2020) analyzed 10 Central and Eastern European and Baltic countries from 2005 to 2016 using FMOLS and VAR models, demonstrating that adjusted net savings are positively correlated with sustainable growth when bolstered by environmental levies that alleviate energy depletion, exhibiting bidirectional causality in certain panels.

Shevchenko et al. (2021) qualitatively examined Ukraine, suggesting that environmental taxes under the European Green Deal might enhance adjusted net savings by aligning with the Sustainable Development Goals, without employing econometric quantification. Tchapchet-Tchouto et al. (2022) examined 31 European countries from 2009 to 2019 using pooled OLS, fixed/random effects, system-GMM, and quantile regression, revealing that environmental taxes exhibit threshold effects on growth indicators, positively correlating with adjusted net savings in high-income groups while negatively affecting low-income groups due to trade-offs. Dradra (2024) analyzed 24 OECD nations from 1994 to 2018 using fixed- and random-effect estimation and quantile regression, demonstrating that environmental taxation fosters sustainable development (including adjusted net savings) by reducing emissions, with positive long-term coefficients influenced by energy transitions. Kukharets et al. (2024) examined EU nations from 2008 to 2022 employing second-order regression models, revealing that environmental tax revenues positively affect renewable energy consumption, thereby indirectly improving adjusted net savings through diminished depletion, with a coefficient of 0.45 for tax revenue on renewable uptake. These findings underscore the significance of environmental taxes in promoting green growth, particularly in Europe, while also stressing the necessity for supplementary policies to mitigate regressive impacts.

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Empirical studies consistently demonstrate a positive correlation between green growth, quantified as adjusted net savings (% GNI), and the share of renewable energy (%), as renewables mitigate depletion and promote sustainability, with the effect more pronounced in developed countries. Acosta et al. (2020) examined 119 nations from 2010 to 2020, revealing that the percentage of renewables enhances the dimension of effective resource utilization, positively influencing adjusted net savings with global increases of approximately 10%. Acosta et al. (2022) evaluated 147 countries from 2010 to 2021 utilizing a composite index with geometric aggregation, revealing that the share of renewable energy positively correlates with adjusted net savings, thereby contributing to moderate global scores, especially in Europe, where elevated shares are associated with a 68-index performance. Koilo et al. (2022) examined 30 European countries from 2012 to 2020 using Data Envelopment Analysis (DEA) and panel regression, discovering that a 1% increase in renewable-related innovation enhances energy efficiency by 0.27%, establishing a positive correlation with adjusted net savings. Wang et al. (2025) examined 14 emerging economies from 1990 to 2022 using convergence methodologies, including Phillips-Sul's club approach. Their findings indicate that renewable electricity generation fosters sustainable development, encompassing adjusted net savings components, whereas non-renewable sources impede it. The study identifies two convergence clubs with policy implications for equilibrium. Furthermore, Shanyazov et al. (2025) found that renewable energy consumption markedly lowers CO_2 emissions in G20 nations, underscoring the environmental advantages of renewable energy transitions across income levels. These findings highlight the role of renewables in promoting green growth across several countries.

Evidence correlating green growth, as measured by adjusted net savings (% GNI), with transport R&D (% GDP) indicates beneficial outcomes through innovation and efficiency; however, research is scarce and frequently employs broader R&D proxies, revealing varied effects depending on development level. Hallegatte et al. (2012) presented a conceptual paradigm devoid of empirical evidence, contending that transport R&D rectifies market failures, hence augmenting adjusted net savings by preventing entrenchment in inefficient infrastructure. Hultman et al. (2016) conducted a descriptive evaluation of global trends from 2005 to 2011, observing that insufficient investment in transport R&D obstructs green growth, and advocating for international collaboration to enhance adjusted net savings in emerging nations. Zakari and Musibau (2024) analyzed OECD countries from 2000 to 2020 via panel ARDL, showing green innovation R&D (including transport) positively correlates with adjusted net savings (bidirectional causality, coefficient 0.22), particularly in high-income nations. Dinh et al. (2025) analyzed 18 developing and 14 developed nations from 2005 to 2021 through Bayesian regression, revealing that R&D expenditure (including transport-related) adversely impacts adjusted net savings in developing countries while positively influencing developed countries, with green finance enhancing these positive interactions. Singh et al. (2025) examined G20 countries from 2000 to 2023 using quantile regression, revealing that transport R&D moderates the relationship between innovation and emissions, enhancing adjusted net savings in high-emission quantiles through improved efficiency. Furthermore, Shanyazov et al. (2026) examined G7 economies from 1990 to 2022 employing a CS-ARDL model, demonstrating that GDP per capita and Trade Openness significantly elevate CO_2 emissions, with long-run elasticities of 0.215 and 0.089, respectively, highlighting the critical role of economic growth and trade in attaining sustainability goals. Collectively, these findings suggest that transport R&D has the potential to enhance green growth, especially in high-income settings.

Based on empirical and theoretical evidence, this study hypothesizes that environmental tax revenues, renewable energy adoption, and transport-related R&D affect green growth, as measured by adjusted net savings (% of GNI). Three gaps remain despite studies showing good connections between the three policy channels and green growth metrics. First, earlier studies mostly examined these channels separately rather than in a framework that allows for their interdependencies. Second, most panel analyses overlook cross-sectional dependence and parameter heterogeneity, which are especially important in an economically connected bloc like the EU. Third, over a period of major policy reforms like the Kyoto Protocol, successive Renewable Energy Directives, and the European Green Deal, EU-27 countries have not systematically addressed the quantile distribution of policy impacts, such as whether environmental taxes, renewable deployment, or transport R&D contribute more at high or low sustainability performance levels.

This study aims to fill all three gaps. We empirically analyze the impact of environmental tax revenues, renewable energy adoption, and transportation research and development expenditures on green growth in EU-27 countries from 2000 to 2024, utilizing a panel CS-ARDL model and MMQR that consider cross-sectional dependence and heterogeneity. Study hypotheses are as follows:

H1: *Environmental tax revenues (% of GDP) have a positive and statistically significant effect on adjusted net savings (% of GNI).*

H2: *The share of renewable energy consumption (%) positively and significantly influences adjusted net savings (% of GNI).*

H3: *Transport-related R&D expenditure (% of GDP) has a positive and statistically significant effect on adjusted net savings (% of GNI).*

2. METHODS

Annual panel data from 27 EU member states, covering 2000 to 2024, are used. Green growth is measured by adjusted net savings, which include particulate emission damage as a percentage of Gross National Income, from the World Bank Development Indicators database (World Bank, n.d.a). After accounting for natural resource depletion and environmental degradation, this comprehensive metric shows real savings, indicating sustainable growth.

From Eurostat Environmental Accounts (Eurostat, n.d.a), environmental tax revenues as a percentage of GDP are the independent variables. Environmental policy's financial aspect includes taxes on energy, transportation, pollution, and resources. Renewable energy adoption is measured by its share of gross final energy consumption, according to Eurostat Energy Statistics (Eurostat, n.d.b). Eurostat Science and Technology Statistics (Eurostat, n.d.c) quantifies transport R&D expenditure as a proportion of GDP, specifically gross domestic expenditure on transport and storage R&D.

The analysis incorporates control variables such as GDP per capita (World Bank, n.d.b) in constant prices to reflect economic development levels, trade openness (World Bank, n.d.c) quantified as the sum of exports and imports as a percentage of GDP, and the urbanization rate (World Bank, n.d.d) indicating the proportion of the population living in urban areas. These control variables mitigate potential confounding effects that may affect both the independent variables and green growth outcomes.

The empirical analysis utilizes a multi-stage econometric methodology, commencing with initial diagnostics and advancing to sophisticated panel estimate approaches. The foundational empirical model is articulated as follows:

$$GG_{it} = \alpha_i + \beta_1 ETR_{it} + \beta_2 REN_{it} + \beta_3 TRD_{it} + \beta_4 X_{it} + \varepsilon_{it}, \tag{1}$$

where GG_{it} signifies green growth for country i at time t, ETR_{it} denotes environmental tax revenues, REN_{it} indicates renewable energy share, TRD_{it} refers to transport R&D expenditure, X_{it} is a vector of control variables, α_i captures country-specific fixed effects, and ε_{it} is the error term.

Due to the extensive economic integration and policy coordination in the European Union, cross-sectional reliance is a significant factor to consider. The analysis utilizes various tests to identify cross-sectional dependence, specifically the Breusch-Pagan LM test (Breusch & Pagan, 1980), the Pesaran CD test (Pesaran, 2004), and the Baltagi, Feng, and Kao test (Baltagi et al., 2012). These tests assess the correlation of disturbances across panel units, hence challenging the independence assumption fundamental to traditional panel estimators.

The study employs the cross-sectionally augmented Im-Pesaran-Shin (CIPS) test, created by

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Pesaran (2007), to assess the stationarity characteristics of variables while considering cross-sectional dependence. This second-generation unit root test enhances conventional unit root tests by incorporating cross-sectional averages to account for common characteristics influencing all nations. The null hypothesis of non-stationarity is evaluated against the alternative hypothesis of stationarity for at least certain cross-sections.

The paper utilizes the Westerlund (2007) error correction-based panel cointegration test, which is resilient to cross-sectional reliance via bootstrap methodologies. This test assesses whether error correction terms in conditional panel error correction models are significantly distinct from zero, hence offering evidence of cointegration relationships. Four test statistics are calculated: G_t, G_a, P_t, and P_a. The group-mean statistics (G_t and G_a) accommodate diverse parameters across nations, whereas the panel statistics (P_t and P_a) aggregate information across cross-sections.

The principal estimation method is the cross-sectionally augmented autoregressive distributed lag (CS-ARDL) model established by Chudik and Pesaran (2015). This method tackles cross-sectional dependence by enhancing typical ARDL models with cross-sectional averages of both dependent and independent variables, therefore encapsulating common determinants and spillover effects. The CS-ARDL model is articulated as follows:

$$\begin{aligned}\Delta GG_{it} &= \phi_i\left(GG_{i,t-1} - \theta_{i0} - \theta_{i1}ETR_{i,t-1}\right.\\ &\left.-\theta_{i2}REN_{i,t-1} - \theta_{i3}TRD_{i,t-1} - \theta_{i4}X_{i,t-1}\right)\\ &+\sum_{j=1}^{p-1}\delta_{ij}\Delta GG_{i,t-j} + \sum_{j=0}^{q-1}\gamma_{ij}\Delta Z_{i,t-j}\\ &+\sum_{l=0}^{r}\lambda_{il}\overline{GG}_{t-l} + \sum_{l=0}^{s}\psi_{il}\overline{Z}_{t-l} + \mu_{it},\end{aligned} \tag{2}$$

where ϕ_i denotes the error correction coefficient, θ coefficients encapsulate long-term correlations, and cross-sectional averages (shown by bars) account for common causes. The model accommodates diverse short-run dynamics and long-run coefficients among countries while considering cross-sectional dependencies. Mean group (MG), pooled mean group (PMG), and dynamic fixed effects (DFE) estimators are utilized to evaluate coefficient heterogeneity.

The study employs the method of moments quantile regression (MMQR) established by Machado and Silva (2019) to analyze heterogeneous impacts throughout the conditional distribution of green growth. In contrast to traditional quantile regression methods, MMQR incorporates fixed effects and addresses endogeneity issues while assessing effects across various quantiles of the result distribution. This facilitates the examination of variations in environmental tax revenues, renewable energy adoption, and transport R&D impacts across nations with differing levels of green growth performance. The MMQR model is defined as follows:

$$\begin{aligned}&Q_{GG}\left(\tau \middle| ETR, REN, TRD, X\right)\\ &= \alpha(\tau) + \beta_1(\tau)ETR + \beta_2(\tau)REN\\ &+\beta_3(\tau)TRD + \beta_4(\tau)X,\end{aligned} \tag{3}$$

where $Q_{GG}(\tau)$ denotes the τ-th conditional quantile of green growth, with β(τ) coefficients differing across quantiles τ∈(0,1). The study calculates coefficients at the 0.10, 0.25, 0.50, 0.75, and 0.90 quantiles to encompass the entire distribution of effects.

3. RESULTS

Table 1 presents descriptive statistics for all variables analyzed across EU-27 nations from 2000 to 2024. The mean adjusted net savings (green growth indicator) stands at 10.12% of GNI, with a standard deviation of 5.73, reflecting considerable cross-country and temporal variation. Environmental tax revenues average 2.53% of GDP, ranging from 0.73% to 5.14%, indicating diverse environmental fiscal strategies among member states. The mean renewable energy share is 22.84%, with a wide range of 1.24% to 72.14%, reflecting the substantial expansion of renewable capacity observed particularly after 2015. Transport R&D expenditure averages 0.41% of GDP with a standard deviation of 0.31, reflecting heterogeneous innovation investment levels across countries.

Table 1. Descriptive statistics

Variable	Mean	Std. Dev.	Min	Max
Green Growth (% GNI)	10.12	5.73	–8.32	29.14
Environmental Tax Revenue (% GDP)	2.53	0.87	0.73	5.14
Renewable Energy Share (%)	22.84	14.93	1.24	72.14
Transport R&D (% GDP)	0.41	0.31	0.02	1.84
GDP per capita (constant US$)	29,834	17,452	4,218	94,218
Trade Openness (% GDP)	98.47	53.24	45.14	412.18
Urbanization Rate (%)	72.14	11.62	47.86	98.74

Note: GG = Adjusted net savings including particulate emission damage (% of GNI); ETR = Environmental tax revenue (% of GDP); REN = Renewable energy share in gross final energy consumption (%); TRD = Transport and storage R&D expenditure (% of GDP); GDPPC = GDP per capita in constant 2015 USD; TO = Trade openness (exports plus imports as % of GDP); URB = Urban population (% of total).

The bivariate correlation matrix is shown in Table 2. Environmental tax revenues are linked to green growth, suggesting that environmental taxation promotes sustainable development. Renewable energy use is positively correlated with green growth, showing that it improves sustainability. Transport R&D expenditure is moderately positively correlated with green growth, suggesting innovative benefits. Environmental tax revenues and the share of renewable energy are positively and significantly correlated, demonstrating that fiscal tools and renewable energy policy complement each other. Variance inflation factors between 1.36 and 2.94, below the conventional threshold of 10, imply that multicollinearity does not affect regression estimates.

Table 3 presents findings from cross-sectional dependence tests, essential for ascertaining suitable econometric parameters. The Breusch-Pagan LM test produces a chi-squared statistic of 2,043.18, decisively rejecting the null hypothesis of cross-sectional independence. The Pesaran CD test statistic is 24.83, indicating substantial cross-sectional dependence. The Baltagi, Feng, and Kao test corroborates these results with a test statistic of 20.17. The results indicate significant cross-sectional reliance among EU-27 countries, possibly due to economic integration, policy coordination via EU regulations, and shared shocks impacting all member states. The presence of cross-sectional dependence requires the use of second-generation panel unit root tests and estimation methods that explicitly account for cross-country interdependencies.

Table 4 displays the outcomes of the cross-sectionally augmented Im-Pesaran-Shin (CIPS) unit root tests, which consider the cross-sectional de-

Table 2. Correlation matrix

Variable	GG	ETR	REN	TRD	GDPPC	TO	URB
GG	1.000						
ETR	0.438	1.000					
REN	0.561	0.483	1.000				
TRD	0.327	0.291	0.208	1.000			
GDPPC	0.401	0.362	0.134	0.573	1.000		
TO	0.221	0.297	0.193	0.349	0.487	1.000	
URB	0.274	0.421	0.097	0.396	0.631	0.363	1.000

Note: GG = Green growth; ETR = Environmental tax revenue; REN = Renewable energy share; TRD = Transport R&D; GDPPC = GDP per capita; TO = Trade openness; URB = Urbanization rate.

Table 3. Cross-sectional dependence tests

Test	Statistic	p-value	Null Hypothesis
Breusch-Pagan LM	2043.18	0.000	No cross-sectional dependence
Pesaran CD	24.83	0.000	No cross-sectional dependence
Baltagi, Feng & Kao	20.17	0.000	No cross-sectional dependence

Note: All tests reject the null hypothesis of cross-sectional independence at the 1% significance level.

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Table 4. Cross-sectionally augmented panel unit root tests (CIPS)

Variable	Level	First Difference	Order of Integration
Green Growth	–1.892	–3.916***	I(1)
Environmental Tax Revenue	–1.714	–3.487***	I(1)
Renewable Energy Share	–1.578	–4.163***	I(1)
Transport R&D	–1.947	–3.724***	I(1)
GDP per capita	–1.823	–3.561***	I(1)
Trade Openness	–2.018	–3.948***	I(1)
Urbanization Rate	–1.671	–3.287***	I(1)

Note: *** indicates rejection of the null hypothesis of non-stationarity at the 1% significance level. Critical values: –2.21 (5%), –2.33 (1%). All tests include trend and constant terms with lag length selected by AIC.

pendence observed in the prior analysis. At all levels, all variables provide CIPS test results that do not reject the null hypothesis of non-stationarity at standard significance levels, signifying the presence of unit roots in the variables. Green growth has a CIPS statistic of –1.892, environmental tax revenue of –1.714, renewable energy share of –1.578, and transport R&D of –1.947, all exceeding the critical value of –2.21 at the 5% significance level. Following the initial differencing, all variables exhibit stationarity, with CIPS statistics much beneath the crucial thresholds. The first differences of green growth show a CIPS statistic of –3.916, environmental tax revenue of –3.487, renewable energy share of –4.163, and transport R&D of –3.724. The results demonstrate that all variables are integrated of order one, I(1), hence validating the application of cointegration analysis and error correction models.

Table 5 presents findings from Westerlund's (2007) error correction-based panel cointegration analyses. The group-mean statistics G_t and G_a evaluate the alternative hypothesis that at least one cross-sectional unit exhibits cointegration, whereas the panel statistics P_t and P_a assess the alternative that the entire panel is cointegrated. The G_t statistic is –3.917, accompanied by a robust p-value of 0.011, while G_a is –12.584 with a *p*-value of 0.026, both indicating the rejection of the null hypothesis of no cointegration. Likewise, P_t results in –16.124 and P_a results in –11.537, offering robust evidence of cointegration linkages. These findings validate the presence of long-term equilibrium linkages among green growth, environmental tax revenues, renewable energy adoption, transport R&D expenditure, and control factors. The existence of cointegration validates the estimation of both short-term dynamics and long-term equilibrium relationships through error correction models.

Table 6 displays estimation outcomes using cross-sectionally augmented autoregressive distributed lag (CS-ARDL) models, detailing both short-run and long-run coefficients. Three estimators are utilized: mean group (MG), pooled mean group (PMG), and dynamic fixed effects (DFE). The Hausman test contrasting PMG and MG estimators produces a chi-squared statistic of 7.82, resulting in a failure to reject the null hypothesis that coefficient differences are not systematic, indicating that the PMG estimator is more efficient while preserving consistency.

Long-run estimates utilizing the PMG estimator reveal that environmental tax revenues possess a positive and statistically significant coefficient of 0.358, signifying that a one percentage point rise in environmental tax revenues relative to GDP correlates with a 0.358 percentage point increase

Table 5. Westerlund panel cointegration tests

Statistic	Value	Robust p-value	Interpretation
G_t	–3.917	0.011	Reject H_0: No cointegration
G_a	–12.584	0.026	Reject H_0: No cointegration
P_t	–16.124	0.006	Reject H_0: No cointegration
P_a	–11.537	0.017	Reject H_0: No cointegration

Note: Robust p-values are based on 1000 bootstrap replications. The null hypothesis is no cointegration. All tests include constant and trend terms with automatic lag selection.

in adjusted net savings as a proportion of GNI in the long term. This study offers robust empirical evidence for the concept that environmental taxation favorably influences green growth outcomes, along with the double dividend theory and Porter and van der Linde's (1995) claim concerning the innovation-inducing impacts of environmental regulation.

The share of renewable energy exhibits a long-run coefficient of 0.531, indicating the most significant positive impact among the principal explanatory factors. This indicates that a one percentage point increase in the renewable energy share correlates with a 0.531 percentage point rise in long-term green growth. This significant impact illustrates the direct environmental advantages of substituting fossil fuel usage and the wider economic benefits of renewable energy implementation, such as less import reliance, technical spillovers, and job creation in sustainable industries.

Transport R&D expenditure exhibits a positive long-term correlation of 0.289, signifying that enhanced investment in innovation within transport sectors substantially contributes to sustainable development results. An increase of one percentage point in transport R&D relative to GDP correlates with a 0.289 percentage point rise in adjusted net savings. This discovery underscores the essential function of technology innovation in enabling decarbonization and enhancing efficiency within the transport sector.

The error correction term is negative and statistically significant at –0.493, suggesting that roughly 49.3% of deviations from long-run equilibrium are rectified within one year. The swift adjustment rate indicates that the interconnections among environmental policies, renewable energy, transport innovation, and green growth are dynamic, with policy alterations and structural modifications resulting in sustainable outcomes within acceptable timeframes.

Short-run coefficients indicate the immediate dynamics of adjustment processes. Environmental tax revenues demonstrate a short-run coefficient of 0.131, signifying positive immediate effects, albeit of lesser magnitude compared to long-run consequences. The share of renewable energy has a short-run coefficient of 0.193, but transport R&D presents a short-run coefficient of 0.098 ($p > 0.10$, not statistically significant), indicating that the benefits of innovation necessitate extended durations to completely manifest.

Table 7 presents the findings from the method of moments quantile regression (MMQR) research, which investigates the variability in the impacts

Table 6. CS-ARDL estimation results

Variable	Mean Group (MG)	Pooled Mean Group (PMG)	Dynamic Fixed Effects (DFE)
Long-Run Coefficients			
Environmental Tax Revenue	0.412*** (0.085)	0.358*** (0.074)	0.301** (0.091)
Renewable Energy Share	0.574*** (0.099)	0.531*** (0.087)	0.483*** (0.101)
Transport R&D	0.327** (0.114)	0.289** (0.094)	0.254* (0.109)
GDP per capita (log)	1.867*** (0.341)	1.694*** (0.293)	1.538*** (0.307)
Trade Openness	0.022* (0.009)	0.021** (0.008)	0.017* (0.009)
Urbanization Rate	0.137** (0.047)	0.121** (0.041)	0.102* (0.044)
Short-Run Coefficients			
ΔEnvironmental Tax Revenue	0.162* (0.065)	0.131** (0.052)	0.114* (0.057)
ΔRenewable Energy Share	0.219* (0.087)	0.193* (0.074)	0.171* (0.080)
ΔTransport R&D	0.118 (0.092)	0.098 (0.079)	0.083 (0.084)
ΔGDP per capita (log)	0.891** (0.281)	0.804** (0.246)	0.736** (0.261)
ΔTrade Openness	0.009 (0.006)	0.008 (0.005)	0.007 (0.006)
ΔUrbanization Rate	0.049 (0.037)	0.043 (0.032)	0.038 (0.034)
Error Correction Term (ECT)	–0.531*** (0.071)	–0.493*** (0.062)	–0.448*** (0.067)
Diagnostic Tests			
Hausman test (PMG vs MG) $\chi^2(6) = 7.82$, p = 0.252			

Note: Standard errors in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.10. All models include country fixed effects and cross-sectional averages to control for common factors. Optimal lag structure selected using AIC with a maximum lag of 2.

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Table 7. Method of moments quantile regression (MMQR) results

Variable	Q (0.10)	Q (0.25)	Q (0.50)	Q (0.75)	Q (0.90)
Environmental Tax Revenue	0.194** (0.071)	0.253*** (0.066)	0.327*** (0.062)	0.432*** (0.069)	0.524*** (0.082)
Renewable Energy Share	0.351*** (0.080)	0.428*** (0.074)	0.507*** (0.069)	0.591*** (0.077)	0.701*** (0.091)
Transport R&D	0.171* (0.089)	0.226** (0.083)	0.274*** (0.077)	0.334*** (0.086)	0.403*** (0.099)
GDP per capita (log)	1.143** (0.337)	1.412*** (0.312)	1.573*** (0.291)	1.761*** (0.324)	1.973*** (0.378)
Trade Openness	0.012 (0.008)	0.015* (0.007)	0.019** (0.007)	0.023** (0.008)	0.028** (0.009)
Urbanization Rate	0.071 (0.046)	0.093* (0.042)	0.112** (0.039)	0.136** (0.043)	0.163*** (0.050)
Constant	–8.547** (2.813)	–10.213*** (2.614)	–11.584*** (2.437)	–13.271*** (2.704)	–15.142*** (3.148)
Pseudo R^2	0.291	0.324	0.353	0.379	0.398

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. All specifications include country and time fixed effects. Estimation uses 1000 bootstrap replications for standard error computation.

of environmental tax revenues, renewable energy adoption, and transport R&D across the conditional distribution of green growth. The analysis encompasses five quantiles (0.10, 0.25, 0.50, 0.75, and 0.90), denoting countries with low, lower-middle, median, upper-middle, and high green growth performance, respectively.

The coefficients for environmental tax income exhibit a monotonic increase over quantiles, spanning from 0.194 at the 10th quantile to 0.524 at the 90th quantile. This pattern demonstrates that the effects of environmental taxation are far more pronounced in nations that have attained advanced levels of green growth, indicating synergies between established sustainability frameworks and fiscal environmental tools. Countries possessing sophisticated environmental management systems, robust institutions, and heightened public environmental consciousness may be more adept at converting environmental tax money into concrete sustainability enhancements.

The fraction of renewable energy demonstrates coefficients that rise over quantiles, ranging from 0.351 at the 10th quantile to 0.701 at the 90th quantile. The continuously favorable and substantial benefits across all quantiles illustrate the strong contribution of renewable energy to green growth outcomes, irrespective of beginning sustainability performance levels. The rise in magnitude at higher quantiles indicates scale effects and learning-by-doing advantages that accumulate as renewable energy sources develop and proliferate.

Transport R&D expenditure has coefficients varying from 0.171 at the 10th quantile to 0.403 at the 90th quantile. The disparate effects across quantiles suggest that investments in innovation produce enhanced sustainability returns in nations with more advanced innovation ecosystems and more capability to commercialize and implement novel transportation technology. This discovery underscores the need for supplementary expenditures in human resources, research facilities, and regulatory frameworks conducive to innovation.

4. DISCUSSION

This study's empirical findings confirm all three hypotheses and demonstrate that environmental tax revenues, renewable energy adoption, and transport R&D investments jointly and positively contribute to green growth in EU-27 countries over 2000–2024. The CS-ARDL and MMQR frameworks, designed explicitly to handle cross-sectional dependence and heterogeneity, yield a richer and more policy-relevant picture than conventional estimators used in much of the prior literature, enabling direct comparisons of magnitude, timing, and distributional variation across the sustainability performance spectrum.

The positive long-term impact of environmental tax revenues on green growth (coefficient of 0.358) indicates that fiscal tools successfully internalize environmental externalities, motivate behavioral modifications, and produce income that may be reinvested in sustainable initiatives. This view endorses the twofold dividend idea, wherein environmental levies alleviate pollution while simultaneously augmenting economic efficiency by diminishing resource depletion and fostering intergenerational justice. The short-run coefficient indicates that immediate effects exist but accumulate over time, perhaps due to adjustment costs faced by industries and families responding to increased taxation. The estimated elasticity aligns with Dradra (2024), who documented long-term coefficients of 0.15–0.25 for the impact of environmental taxation on sustainable development in OECD nations, highlighting emission reductions as a mediating variable. Kukharets et al. (2024) similarly identified a coefficient of 0.45 for the indirect influence of tax revenues on renewable energy use in EU countries, which subsequently enhances adjusted net savings, aligning with the direct positive correlation identified here. The findings, however, surpass those of Abdullah and Morley (2014), who established a long-term causal relationship from sustainable growth to environmental taxes within the EU and OECD frameworks, with negligible reverse effects; bidirectional dynamics are illustrated via the error correction mechanism, exhibiting an adjustment rate of 49.3%. Unlike Tchapchet-Tchouto et al. (2022), who identified threshold effects with adverse consequences for low-income groups, the MMQR analysis demonstrates consistently increasing effects across quantiles (ranging from 0.194 at the 10th to 0.524 at the 90th), suggesting that environmental taxes are especially effective in high-performing sustainability contexts, likely attributable to more robust institutional frameworks in advanced EU economies. This heterogeneity underscores the need for customized policies to prevent regressive burdens, as noted by Batrancea et al. (2020) for Central and Eastern European nations, where positive correlations were identified but further action was needed to mitigate energy depletion. Moreover, Shanyazov et al. (2026) demonstrated that geopolitical risk and policy uncertainty significantly exacerbate CO_2 emissions in G7 economies, suggesting that the effectiveness of environmental fiscal instruments may be moderated by political stability and policy coherence across EU member states.

The adoption of renewable energy is the most significant predictor of green growth, exhibiting a long-run elasticity of 0.531, which indicates its effectiveness in diminishing fossil fuel reliance, decreasing emissions, and enhancing resource efficiency. The short-run effect implies incremental integration advantages, possibly constrained by initial infrastructure expenditures, and the swift mistake correction signifies effective policy transmission. This outcome views renewable energy as a fundamental component of sustainability governance, facilitating decarbonization in transportation and other sectors. The coefficient surpasses the indirect improvements identified by Acosta et al. (2022), who associated elevated renewable shares with enhanced global green growth indices (approximately 68 in Europe), and Acosta et al. (2020), who projected roughly 10% global increases in resource utilization metrics related to renewables. Koilo et al. (2022) documented a 0.27% increase in efficiency for every 1% increase in renewable energy use in European nations, which corresponds to the overall sustainability effect on adjusted net savings. Moreover, Wang et al. (2025) recognized that renewable energy promotes convergence in sustainable development among emerging economies, in contrast to the hindrances posed by non-renewable sources, a trend reflected in the positive causality analysis focusing on the EU. The MMQR results indicate increasing effects across quantiles (0.351 at the 10th to 0.701 at the 90th), implying scale economies and learning effects in high-adoption countries, which may elucidate the more significant advantages relative to the moderate correlations observed in less developed regions, as emphasized by these studies. The findings substantiate the literature's agreement on the beneficial impact of renewables while offering detailed quantile insights that were previously unaddressed.

Transport R&D expenditures exhibit a substantial long-term positive correlation with green growth (coefficient of 0.289), indicating that investments in innovation stimulate technological progress, including electric vehicles and intelligent systems, thereby improving efficiency and mitigating environmental harm. The negligible short-term effect (0.098) suggests a delayed realization, aligning with the time-consuming process of R&D commercialization. This approach regards transport innovation as a key facilitator for dissociating economic growth from emissions, tackling market inefficiencies in infrastructure as articulated by Hallegatte et al. (2012).

The findings also align with those of Zakari and Musibau (2024), who reported a 0.22 coefficient for green innovation R&D (including transport) in OECD nations, exhibiting bidirectional cau-

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sation in high-income environments mirroring the EU situation. Dinh et al. (2025) indicated favorable outcomes in industrialized countries but adverse consequences in underdeveloped nations, which corresponds with the quantile heterogeneity (0.171 at the 10th percentile to 0.403 at the 90th percentile), implying more substantial returns in innovation-mature economies. This expands upon Singh et al. (2025), who observed the moderating influence of transport R&D on emissions reduction in high-emission quantiles within G20 nations, and enhances the descriptive findings of Hultman et al. (2016) which recommended augmenting R&D to avert inefficiency lock-ins, albeit lacking quantitative assessments. This paper addresses a deficiency in the limited transport-specific literature by presenting substantial panel evidence, underscoring the necessity for strategic expenditures to enhance sustainability results.

CONCLUSION

This study aims to assess the impact of renewable energy adoption, environmental tax revenues, and transport R&D expenditures on green growth across EU-27 from 2000 to 2024. Three main findings emerge from the analysis. First, green growth is positively affected by all three policy channels, with long-run PMG elasticities of 0.358 for environmental taxation, 0.531 for renewable energy adoption, and 0.289 for transport R&D. The magnitudes order according to each mechanism's direct link to emission reduction and each sector's policy maturity. Second, approximately 49% of deviations from long-term equilibrium are corrected within one year, indicating that policy effects occur within a relevant timeframe rather than over generations (error-correction value = –0.493). Third, MMQR estimates show significant quantile heterogeneity: coefficients increase consistently from the 10th to the 90th percentile for all three regressors, suggesting that countries with strong environmental governance frameworks benefit more from sustainability policy in terms of fiscal and innovation returns.

These findings have three policy implications. Policy efficacy quantile gradients show that earlier investments in environmental infrastructure and institutions yield compounding gains, suggesting a front-loaded green transition rather than a gradual strategy. The strong cross-sectional dependence among EU economies, confirmed by Breusch-Pagan LM, Pesaran CD, and Baltagi-Feng-Kao statistics (all rejecting independence at the 1% significance level), suggests that uncoordinated national policies cause negative spillovers and missed opportunities. Therefore, EU-level initiatives like the ETS extension and the Social Climate Fund are both politically appealing and empirically necessary. Transport R&D's modest but notable contribution and statistically insignificant short-term coefficient highlight the need for innovation policy to secure patient, long-term public funding commitments that are shielded from electoral cycles, especially in underperforming economies like Central and Eastern Europe, where institutional capacity to absorb and commercialize R&D is still limited.

The conclusions lead to policy suggestions. Environmental taxes should be broadened in scope and rate, especially through carbon pricing systems, and revenue reinvested to offset distributional consequences across member states. To achieve sustainable savings at the expected elasticity of 0.531, RED III renewable energy goals require faster licensing reforms and grid investments. Due to innovation's green growth dividend and long-term rewards, transport R&D funds, especially in Horizon Europe and national research councils, should be protected against short-term budgetary constraints. Cohesion policy instruments must continuously link structural fund allocations to green growth performance to accelerate quantile convergence and prevent lower-performing member states from being disadvantaged in the green transition.

These conclusions have major consequences for European climate neutrality by 2050. The analysis shows that green growth policy instruments are available and work within EU legislative and budgetary cycles.

An error correction rate of 49% per year shows that sustained policy commitment will lead to green development advances in 10 years, which matches the European Semester and Multiannual Financial Framework planning periods.

Future research should examine sector-specific environmental policies, green transition programs' distributional effects across income groups and regions, and how behavioral and social factors affect policy performance. A non-EU comparison would show how institutional and economic factors affect environmental policies and sustainable development. To assess the long-term effects of the European Green Deal, the Carbon Border Adjustment Mechanism, and the 2035 CO_2 standards for passenger vehicles, it is necessary to revise these estimates with post-2024 data. Such studies will be essential for formulating effective, equitable, and politically feasible plans for global sustainability transitions.

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