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Panel data analysis of energy transition, circular economy and green innovation as drivers of environmental sustainability in the European Union

M. Naeem

Department of Mathematics and Computer Science, Modern College of Business and science, Oman

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ABSTRACT

BACKGROUND AND OBJECTIVES: This study examines the determinants of environmental sustainability within 27 European Union countries from 2014 to 2024, capturing the impact of critical structural and policy changes. This study systematically examines five dimensions of sustainability. It first determines the influence of energy transition variables on per capita carbon emissions, subsequently examines the effect of circular economy strategies on resource productivity and finally evaluates the non-linear link between economic growth and carbon dioxide emissions is identified using the Environmental Kuznets Curve framework. The study objectives were to explore five empirical models concerning the European Unions-27 countries and the impacts of the energy transition on per capita carbon emissions and role of circular economy in enhancing resource efficiency. Additionally, it tests the validity of the Environmental Kuznets Curve theory and income turning point.

METHODS: A complete panel data set that comprises 297 country year observations is used. The empirical methodology is based on robust fixed effects regression models. Principal component analysis is used on six standardized variables. Principal component analysis serves as a robust statistical framework for constructing environmental sustainability index. The socio-economic factors affecting environmental sustainability index are further analyzed. Validation of the model through diagnostic tests is performed.

FINDINGS: Renewable energy consumption mitigates carbon dioxide emissions, while energy intensity and environmental tax revenues emerge as critical determinants of sustainability. The presence of strong empirical evidence in support of the inverted-U shape of the Environmental Kuznets Curve theory is confirmed. These findings indicate that most European Unions' member have progressed to the declining phase of the curve. According to the composite index, Sweden, Finland, and Austria belong to the best performers. Simultaneously, the lowest performance ratings are observed in Malta, Romania, and Cyprus.

CONCLUSION: Offering critical empirical insights for European policymakers, this evidence underscores the need to prioritize reductions in energy intensity while supporting the strategic utilization of fiscal environmental mechanisms. Implementation of targeted green transition frameworks is highly recommended.

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*Corresponding Author:
Email: naeem787@gmail.com
Phone: +968 9730 5945
ORCID: 0000-0002-9071-1708

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INTRODUCTION

Environmental sustainability is one of the main issues of the present time, and the European Union (EU) has managed to take a leading role in the struggle against climate change and sustainable development on a global scale. The European green deal (EGD), introduced in December 2019, is the ambitious strategy of the EU aimed at making Europe the first climate-neutral continent by 2050 (European Commission, 2019). The Green Deal encompasses diverse policy areas, specifically targeting energy sector decarbonization, the promotion of circular economy (CE) principles, environmental enhancement, and the stimulation of green innovation. One of the objectives of the Green Deal for the next decade is to reduce net greenhouse gas emissions by at least 55 percent (%) by 2030 compared to 1990 (European Commission, 2021). Although the EU maintains a cohesive strategic framework, significant disparities remain apparent across individual member states' environmental records. While countries like Sweden and Finland have demonstrated significant successes in their use of renewable energy sources and reductions in carbon emissions, some countries in Eastern Europe, which are also members of the Union, remain highly dependent on fossil fuels and experience severe environmental problems (Pylak *et al.,* 2024) These differences are apparent in the most recent Eurostat data, which reveals wide discrepancies between countries' use of renewable energy sources (from less than 10% in Malta to almost 60% in Sweden) and carbon dioxide (CO_2) emissions per capita (Sixfold discrepancy across the EU-27) (Eurostat, 2024). The theories foundation of this study draws upon established principles within the field of environmental economics. According to the Environmental Kuznets Curve (EKC) hypothesis, there exists a negative relationship between economic development and environmental degradation, implying that at early stages, pollution levels grow as income rises, but later, decrease due to introduction of clean technologies and environmental policies (Grossman and Krueger, 1991). The Porter hypothesis posits that stringent environmental regulations can stimulate innovation and enhance competitiveness, thereby yielding mutually beneficial outcomes for both ecology and the economy (Porter and van der Linde, 1995). Moreover, the theory of directed technical change highlights the possibility of directing innovation to environmentally friendly technologies with the help of appropriate policy tools (Acemoglu *et al.,* 2012). This study contributes significantly to the existing literature in environmental economics in several keyways. First, a comprehensive panel database of 27 EU member states is created for an 11-year period from 2014 to 2024. This database integrates key metrics reflecting energy transition, the circular principles economy, and environmental quality. Additionally, indicators tracking the green economy and socio-economic development are included. This approach captures both cross-country variations and temporal dynamics within a unified dynamic. Second, the use of fixed effects (FE) panel regression models helps to account for the unobserved heterogeneity and test five different research hypotheses that are interrelated. Third, an ESI is developed via principal component analysis (PCA), providing a framework to rank and evaluate cross-country performance The current study makes four distinct contributions to existing literature. First, unlike prior studies that examine energy transition, circular economy, or green innovation in isolation (Armeanu *et al.,* 2017; Simion *et al.,* 2025; Ahmed *et al.,* 2019), By utilizing a unified panel framework for the EU-27, this study systematically evaluates all five dimensions to provide a comprehensive analysis of environmental sustainability drivers. Second, the study period (2014-2024) captures the implementation of major EU environmental policies including the European Commission,

(2019), the Coronavirus 2019 (COVID-19) pandemic (2020-2021), and the European Commission, (2022) offering the first empirical assessment of these policy impacts. Third, methodologically, a system generalized method of moments (GMM) approach (Blundell and Bond, 1998) is employed alongside fixed-effects regression to address endogeneity concerns. Additionally, Driscoll and Kraay (1998) robust standard errors are estimated to adjust for cross-sectional dependence (CD) among EU member states. Fourth, an ESI is constructed utilizing principal component analysis (PCA), with its diagnostic validity confirmed via the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's test. Furthermore, bootstrap confidence intervals are computed for the Environmental Kuznets Curve (EKC) turning point, ensuring methodological rigor. The selection of the 2014-2024 study period is grounded in several policy milestones. The year 2014 marks the launch of the 2030 climate and energy framework (European Commission, 2014), which established binding targets for renewable energy and greenhouse gas reductions. With the introduction of the 2015 Circular Economy Action Plan, the European Commission (2015) launched its first comprehensive strategy for resource efficiency. The 2019 EGD (European Commission, 2019) set the ambition of climate neutrality by 2050, while the COVID-19 pandemic in 2020-2021 created both environmental disruptions and green recovery opportunities. Finally, the 2022 REPowerEU strategy responded to the Russia-Ukraine energy crisis with accelerated renewable energy deployment targets. To account for these structural breaks, COVID-19 (2020-2021) and energy crisis (2022-2024) dummy variables are included in all regression models. The nexus between renewable energy consumption and carbon emissions has been extensively examined in environmental economics literature. The theory underlying the connection comes from the concept of substitution effects as the rise in the use of renewable energy results in lower fossil fuel energy use; thus, there will be lower greenhouse gas emissions as a result. Utilizing a panel Granger causality test, Armeanu *et al*. (2017) examined the causal relationships among total energy consumption, renewable energy deployment, and CO_2 emissions across the EU countries, demonstrating that renewable energy significantly mitigated carbon emissions, particularly after 2010. This research analyzed 27 EU member states in the period of 1990-2014. Insights into the dynamics of CO_2 emissions in Europe in the context of the COVID-19 era were provided by Jawadi *et al.* (2023), who used annual data of 25 European countries from 2010 to 2020. The findings demonstrate that emissions are highly sensitive to volatility in oil and coal prices, while also being influenced by underlying production cycles. Particularly, the authors revealed that investment in sustainable development and the use of renewable energy have a substantial negative effect on CO_2 emissions. Regarding country-level evidence, Shahbaz *et al.* (2016) showed that one percent growth of renewable energy consumption causes approximately 0.15 percent reduction of carbon emissions in developed countries, taking Malaysia as a case study with the help of stochastic impacts by regression on population, affluence, and technology (STIRPAT) model. Kongkuah and Alessa (2025) analyzed data for 184 countries and proved that the efficiency of renewable energy policies is determined not only by the existing energy structure but also by institutional environment. This suggests that the EU strategy of establishing differentiated renewable energy targets based on member states' varying baseline conditions is empirically grounded. Additionally, the mediating role of digitalization has been examined within the context of energy consumption and emissions dynamics. A study by Dimian *et al.* (2026) has investigated the influence of digitalization on greenhouse gas emissions through renewable energy consumption in EU-27 countries from 2000 to 2021, revealing that digitalization reduces greenhouse gas emissions via renewable energy pathways. The mediation analysis underscores

that digital technologies are essential for implementing the green energy transition, which gained pivotal importance within the REPowerEU framework in the wake of the 2022 energy crisis. The CE approach, which is characterized by waste reduction, recycling, and resource efficiency, has attracted attention in the EU policymaking process due to the approval of the Circular Economy Action Plan of 2015 and another one in 2020. Geissdoerfer *et al.* (2017) defined the CE as the regenerative approach that reduces resource consumption and waste generation while ensuring economic performance. Systematic reviews by Hereu-Morales *et al.* (2024) and Stefanis *et al*. (2024) establish that the CE model operates as a distinct sustainability framework rather than a conventional waste management approaches, a perspective corroborated by Simion et *al*. (2025) through their analysis of CE indicators. On resource efficiency in EU member states during 2012–2023 based on panel quantile regression analysis. According to their findings, there are notable differences between the impact of investments, gross value added, patents, material footprint, and circular material use rate on resource efficiency in various parts of the distribution. The findings indicate that while capital investments exert a more pronounced impact at lower levels of resource productivity, patent-based innovation plays an essential role at higher productivity thresholds. The highest resource efficiency was achieved in the Netherlands, Italy, and Luxembourg, while Finland, Bulgaria, and Romania had the lowest values. The monitoring framework of the EU's CE was introduced by the European Commission (2018) through indicators such as material footprint, resource productivity, waste generation, recycling and circular material use rate. Studies using the methodology of preference ranking organization method for enrichment evaluations (PROMETHEE) have indicated that the five countries ahead in terms of CE are Germany, France, Italy, the Netherlands and Spain while those having the most difficult conditions are Cyprus, Romania, Estonia, Finland and Bulgaria (Remeikienė *et al.,* 2025). Circular material use rate in the EU in 2023 is reported to have reached 11.8% as against the goal of 23.4 % in 2030. Over the last decade, the EU's CE policy framework has undergone substantial transformation. The amendment to the Waste Framework Directive in 2018 included targets of 65% recycling and preparation for reuse of municipal waste until 2035 and a maximum of 10% landfilling (Fitch-Roy *et al.,* 2019; Shetty *et al.,* 2025). These legislative adjustments marked a structural shift from traditional linear end-of-pipe waste disposal toward a closed-loop circular economy framework within the European Union. Under the directive's October 2025 revision, extended producer responsibility schemes for the textile sector have become compulsory, alongside optimized reporting regulations (Boschmeier *et al.,* 2023; Paleari, 2025). These mandatory frameworks compel manufacturers to finance end-of-life sorting and fiber-to-fiber recycling networks, altering the operational landscape of the fast fashion industry. This forms the policy backdrop for analysis of CE indicators and resource productivity. According to the EKC theory, which was put forward by Grossman and Krueger (1991) in their groundbreaking paper on the environmental consequences of the North American Free Trade Agreement, there exists an inverse-U curve relationship between economic growth and environmental degradation. The theory is grounded in the premise that during early developmental phases, rising incomes correlate with increased pollution due to rapid industrialization and the prioritization of economic growth over environmental concerns. However, after reaching a particular level of income, there arises a desire for clean environments, and as such, emissions decrease despite growing gross domestic product (GDP). The early empirical research carried out by Shafik and Bandyopadhyay (1992) and Panayotou (1993) offered inconsistent findings regarding the validity of the EKC hypothesis based on pollutants and

countries studied. Specifically, Shafik and Bandyopadhyay (1992), demonstrated that the relationship between income and environmental degradation depends heavily on the specific pollutant examined, noting an inverted U-shaped relationship for sulfur dioxide alongside monotonic relationships for alternative pollutants. Panel data analysis conducted recently by Kaika and Zervas (2013) and Ahmed *et al*. (2019) on developed countries has found stronger support for the EKC, with the turning point coming in per capita GDP levels from Euro (EUR) 17,585 to EUR 35,170. In terms of the EU, the applicability of EKC is especially relevant since there is great disparity in GDP per capita across EU countries, ranging from more than EUR 96,717for Luxembourg to less than EUR 21,981 for Bulgaria. An extensive study on environmental sustainability in connection with the EGD demonstrated that, although the general trend supports the Environmental Kuznets Curve (EKC) hypothesis, considerable disparities exist across different policy measures and groups of countries. Crucially, the analysis concludes that EGD efficacy hinges upon whether poorer member states receive the necessary structural support to leapfrog traditional, high-emission stages of economic development. EKC research has also progressed to include other factors apart from income into its framework. Some of the factors considered in recent literature have been energy mix, trade liberalization, foreign direct investments, institutional quality, and technological innovations. The empirical consensus indicates that the EKC effect is contingent upon the policy decisions and institutional frameworks, rather than being an intrinsic outcome of economic development per se. Such a conditional EKC model has several implications in terms of EU policies, as they show that active environmental policies could bring down the turning point. Green innovation, which consists of research and development research and development (R&D) investments, green patents, and environmentally sound technological changes, is a significant factor in promoting sustainability. Acemoglu *et al*. (2012) underscored the importance of technical change in environmental shifts, arguing that carbon taxes and subsidies for R&D on environmentally friendly innovations would redirect innovation from carbon-heavy industries. They illustrate that transient policy interventions can generate path-dependent, permanent effects by shifting technological trajectories and lowering long-term environmental mitigation costs. Ghisetti and Rennings (2014) explored the link between environmental innovations and profitability based on the data from the German innovation survey and found that environmental policies, especially environmental tax policies, promote green innovation and environmental quality. Environmental innovations are broadly categorized into process and product innovations; the former aims to reduce resource depletion and environmental emissions, while the latter centers on creating ecologically superior products. The authors conclude that the Porter Hypothesis was supported in the case of environmental regulations. However, Rubashkina *et al*. (2015) have pointed out that there is a complicated relationship between innovation and environment which can imply significant time lags. The analysis of European manufacturing industries has shown that while the impact of environmental regulation on innovation is positive, environmental achievements can emerge only after several years. As the above-mentioned time aspect is especially important for the case in point, it should be noted that the 2014-2024 period encompasses implementation of newre EU environmental policies, including the 2030 Climate and Energy Framework and EGD. Environmental taxation has been extensively studied as a policy instrument for fostering eco-innovation. Data from Eurostat reveal that environmental tax revenue in the EU reached EUR 341.5 billion in 2023, constituting 2.0% of GDP and 5.1% of total government revenue from taxes and social contributions (Eurostat, 2024). Almost four-fifths of environmental tax revenue were comprised by

energy taxes, CO_2-related taxes having risen from EUR 15 billion in 2017 to more than EUR 50 billion in 2023. This financial mechanism serves a dual purpose: acting as an economic disincentive for pollution while simultaneously channeling revenues back into innovation support. The bibliometric analysis on the topic of environmental sustainability in relation to the European Green Deal (EGD) by Stefanis *et al.* (2024) revealed that for ecological sustainability and the realization of the ambitious goals of the green deal, significant actions must be made through policy, innovation, and investment in green technologies. In the domain of cleaner energy systems, this technological push is exemplified by the integration of explainable machine learning architectures to accurately predict CO_2 deposition conditions during cryogenic processing (Hsu *et al.,* 2025). Furthermore, executing these policy and technological goals successfully requires robust structural modeling to mitigate corporate greenwashing, thereby ensuring that industrial investments yield genuine environmental benefits (Daga *et al.,* 2025). The study emphasizes that the impact of green innovation elements varies across EU member states, reflecting the complex relationships between economic development, innovation potential, and environmental outcomes. Considering these facts, the study uses multi-faceted approach that analyses green innovation along with energy transition and CE indices. This study aims to evaluate five key empirical dimensions across the EU-27' first, to analyze the impact of the energy transition on per capita carbon emissions; and second, to assess the circular economy's contribution to resource productivity; third, to test the validity and income turning point of the EKC hypothesis; fourth, to quantify the impacts of green innovation and environmental taxation on fine particulate matter ($PM_{2.5}$), and overall air quality metrics and finally, to identify the socio-economic determinants of a PCA-constructed ESI for cross-country benchmarking. This study analyzed 27 EU member states in the period of 1990-2014 and performed in Oman which is performed in 2026.

MATERIALS AND METHODS

Data sources and variables

This study uses a balanced panel dataset which covers 27 member countries of EU between the years 2014 and 2024 (297 observations). The dataset is collected from Eurostat, which is the statistical office of the EU, in addition to World Bank Development Indicators. This specific timeframe was selected to account for the impact of major EU environmental policies, including the circular economy initiatives and regulatory frameworks established by the European Commission (2014, 2015, 2019, 2022). It is worth noting that the UK is not included in this sample after its exit from the EU in 2020. The variables have been classified in five conceptually distinct classes. Energy transition variables comprise the share of renewable energy in gross final energy consumption (%), energy intensity measured in megajoules per United States Dollar (USD) GDP at purchasing power parity (PPP), and the renewable electricity share of total electricity production (%). CE related variables comprise the recycling rate of municipal waste (%), and resource productivity (measured in Euro per kilogram (kg) of materials consumed). Environmental quality metrics are captured by $PM_{2.5}$ air pollution exposure in microgram per cubic meter ($\mu g/m^3$), CO_2 emission, and total forest cover as a percentage of land area. The green economy variables consist of environmental goods and services sector (% of GDP), and environmental tax revenue (% of total tax revenue). Lastly, socio-economic control variables are GDP per capita PPP, constant 2021 international USD, and R&D expenditure (% of GDP).

Econometric models

The FE panel regression models were employed to account for unobserved country-specific heterogeneity that may be correlated with the independent variables. Based on the Hausman

test, which consistently rejects the null hypothesis of no correlation between country-specific effects and the regressors (Eq. 1), the FE approach is preferred over the random effects model (Baltagi, 2021):

$$Y_{it} = \alpha + \sum_{j=1}^{k} \beta_j X_{jit} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

Where: Y_{it} is the dependent variable for country i at time t, X_{jit} are the independent variables, μ_i represents country fixed effects, λ_t represents year fixed effects, and ε_{it} is the error term. Heteroskedasticity-robust standard errors are used to address potential violations of homoskedasticity.

Model 1 examines the impact of energy transition on carbon emissions, using Eq. 2 (Busu and Nedelcu, 2021):

$$\text{CO2}_{it} = \alpha + \beta_1 \text{REN}_{it} + \beta_2 \text{EI}_{it} + \beta_3 \text{REN_ELEC}_{it} + \beta_4 \text{GDP}_{it} + \beta_5 \text{R\&D}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

Model 2 assesses the CE determinants of resource productivity, using Eq. 3 (Simion *et al.*, 2025):

$$\text{RES_PROD}_{it} = \alpha + \beta_1 \text{RECYCLE}_{it} + \beta_2 \text{EGSS}_{it} + \beta_3 \text{ENV_TAX}_{it} + \beta_4 \text{GDP}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

Model 3 tests the Environmental Kuznets Curve hypothesis, using Eq. 4 (Odei *at al.*, 2025):

$$\text{CO2}_{it} = \alpha + \beta_1 \text{GDP}_{it} + \beta_2 \text{GDP}_{it}^2 + \beta_3 \text{REN}_{it} + \beta_4 \text{EI}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

Model 4 evaluates green innovation effects on environmental quality, using Eq. 5 (Aneja *et al.*, 2024):

$$\text{PM2.5}_{it} = \alpha + \beta_1 \text{R\&D}_{it} + \beta_2 \text{EGSS}_{it} + \beta_3 \text{ENV_TAX}_{it} + \beta_4 \text{REN}_{it} + \beta_5 \text{GDP}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (5)$$

Model 5 constructs and explains the composite ESI, using Eq. 6 (Jain and Mohapatra, 2023):

$$\text{ESI}_{it} = \alpha + \beta_1 \text{GDP}_{it} + \beta_2 \text{R\&D}_{it} + \beta_3 \text{ENV_TAX}_{it} + \beta_4 \text{EGSS}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (6)$$

ESI is constructed using PCA on six standardized variables: renewable energy share, recycling rate, resource productivity, forest area, inverted $PM_{2.5}$ exposure, and inverted CO_2 emissions. PCA is a dimensionality reduction technique that transforms correlated variables into a set of uncorrelated principal components. To construct the composite index, the first principal component was retained, as it explains the largest proportion of total variance. This approach has been widely used in sustainability index construction, as it avoids subjective weighting while capturing the common variation across environmental indicators.

Diagnostic tests

To ensure the robustness of the empirical findings, several diagnostic tests were performed. These include the Jarque-Bera test for normality of the residual term, the Durbin Watson statistic for first-order autocorrelation, and the variance inflation factor (VIF) for the detection of multicollinearity amongst the regressors. Additionally, the Pesaran (2021) cross-sectional dependence (CD) test is reported to account for correlated error structures across EU countries. Furthermore, the Levin-Lin-Chu (LLC) panel unit root test is utilized to establish stationarity, alongside the Wooldridge test for serial correlation and the Breusch-Pagan test for heteroskedasticity. To address CD in inference, Driscoll and Kraay (1998) standard errors are reported as the primary method. Furthermore, to mitigate potential endogeneity concerns and ensure the validity of our findings, a System GMM (Blundell and Bond, 1998) estimation is employed as a robustness check Furthermore, the empirical strategy includes subgroup analyses to contrast the EU-15 and newer EU-13 cohorts, the

estimation of lagged specifications to account for temporal policy delays, and the calculation of bootstrap confidence intervals for the EKC turning point. Other statistics that will be reported include the F-statistics for the joint significance of the explanatory variables and the adjusted R-squared measure of goodness of fit.

RESULTS AND DISCUSSION

Descriptive statistics and correlation analysis

Table 1 presents the descriptive statistics for all variables used in the analysis. The average renewable energy share across EU-27 stands at 23.29%, though substantial cross-country variation exists, ranging from a low of 4.38% in Malta to a high of 58.73% in Sweden. CO_2 emissions per capita average 5.83 metric tons, with Luxembourg (14.59 tons) and Estonia showing the highest levels. The average PM2.5 exposure is 11.27 micrograms per cubic meter ($\mu g/m^3$), well above the World Health Organization (WHO) guideline of 5 $\mu g/m^3$, highlighting the continued air quality challenges in the EU. Given the presence of CD confirmed by Pesaran CD tests. To address potential endogeneity from bidirectional causality, system GMM (Blundell and Bond, 1998) is employed as a robustness check. COVID-19 (2020-2021) and energy crisis (2022-2024) dummies are included in all models to account for structural breaks. The correlation matrix given in Table 2 highlights several important correlations. The proportion of renewable energy usage has negative correlations with CO_2 emission (r = -0.37) and PM2.5 pollution (r = -0.60), indicating that those nations which use more renewable energy enjoy environmental benefits as well. Environmental taxes have strong positive correlations with resource efficiency (r = 0.84) and recycling ratio (r = -0.22), highlighting the efficiency of fiscal policies. Per capita GDP has positive correlations with resource productivity (r = 0.84) and R&D spending (r = 0.44). Fig. 1 displays the correlation heatmap for all analyzed variables, illustrating the respective bivariate relationships. The intensity of the color shading corresponds to the magnitude of the correlation coefficients, where red denotes a positive association and blue signifies a negative relationship, thereby facilitating visual interpretation of interactions.

Model 1: Energy transition and carbon emissions

Table 3 outlines the empirical results for Model 1, demonstrating that the energy transition indicators exert a significant impact on carbon emission levels. The variable of the share of renewable energy has a statistically significant and negative beta value (-0.052, $p < 0.10$), indicating its adverse influence on sustainability. Specifically, a one-percentage-point increase in the share of renewable energy is associated with a 0.052-ton reduction in per capita CO_2 emissions. This finding aligns with the empirical evidence reported by Jawadi *et al.* (2023).

Table 1: Descriptive statistics of environmental sustainability variables

Variable	N	Mean	Standard deviation (SD)	Min.	Max.	Skew
Renewable energy share (%)	297	23.29	11.94	4.38	58.73	0.85
Energy intensity (MJ/€GDP)	297	3.38	0.73	1.76	5.61	0.26
Renewable electricity (%)	297	34.38	17.71	4.93	81.28	0.54
Recycling rate (%)	297	39.51	14.54	4.93	68.66	-0.36
Resource productivity (EUR/kg)	297	2.33	0.78	0.81	4.09	0.27
$PM_{2.5}$ exposure ($\mu g/m^3$)	297	11.27	3.31	3.88	19.73	-0.09
CO_2 emissions per capita (tons)	297	5.83	2.44	2.45	14.59	1.32
Forest area (% of land)	297	35.16	16.79	1.02	76.35	0.42
Env. goods and services (%GDP)	297	2.56	0.59	1.46	4.06	0.40
Environmental tax (%total)	297	7.11	0.91	4.99	9.78	0.13
GDP per capita (USD, PPP)	297	39,490	17,358	17,292	111,127	1.89
R&D expenditure (% GDP)	297	2.03	0.92	0.49	4.16	0.48

Table 2: Pearson correlation matrix of environmental sustainability variables

Variable	REN	EI	REL	REC	RPR	PM25	CO_2	FOR	EGS	ETX	GDP	RD
REN	1.00	-0.11	0.79	0.27	0.06	-0.60	-0.37	0.68	0.50	0.29	-0.13	0.47
EI	-0.11	1.00	-0.37	-0.23	-0.57	0.49	0.25	0.26	-0.45	0.30	-0.47	-0.28
REL	0.79	-0.37	1.00	0.32	0.19	-0.41	-0.44	0.36	0.53	0.18	-0.01	0.42
REC	0.27	-0.23	0.32	1.00	0.75	-0.42	0.24	0.27	0.73	-0.22	0.53	0.81
RPR	0.06	-0.57	0.19	0.75	1.00	-0.52	0.32	-0.09	0.80	-0.38	0.84	0.73
PM_{25}	-0.60	0.49	-0.41	-0.42	-0.52	1.00	0.05	-0.38	-0.65	0.21	-0.40	-0.51
CO_2	-0.37	0.25	-0.44	0.24	0.32	0.05	1.00	-0.02	0.05	-0.17	0.53	0.11
FOR	0.68	0.26	0.36	0.27	-0.09	-0.38	-0.02	1.00	0.25	0.12	-0.11	0.37
EGS	0.50	-0.45	0.53	0.73	0.80	-0.65	0.05	0.25	1.00	-0.07	0.49	0.90
ETX	0.29	0.30	0.18	-0.22	-0.38	0.21	-0.17	0.12	-0.07	1.00	-0.52	-0.12
GDP	-0.13	-0.47	-0.01	0.53	0.84	-0.40	0.53	-0.11	0.49	-0.52	1.00	0.44
RD	0.47	-0.28	0.42	0.81	0.73	-0.51	0.11	0.37	0.90	-0.12	0.44	1.00

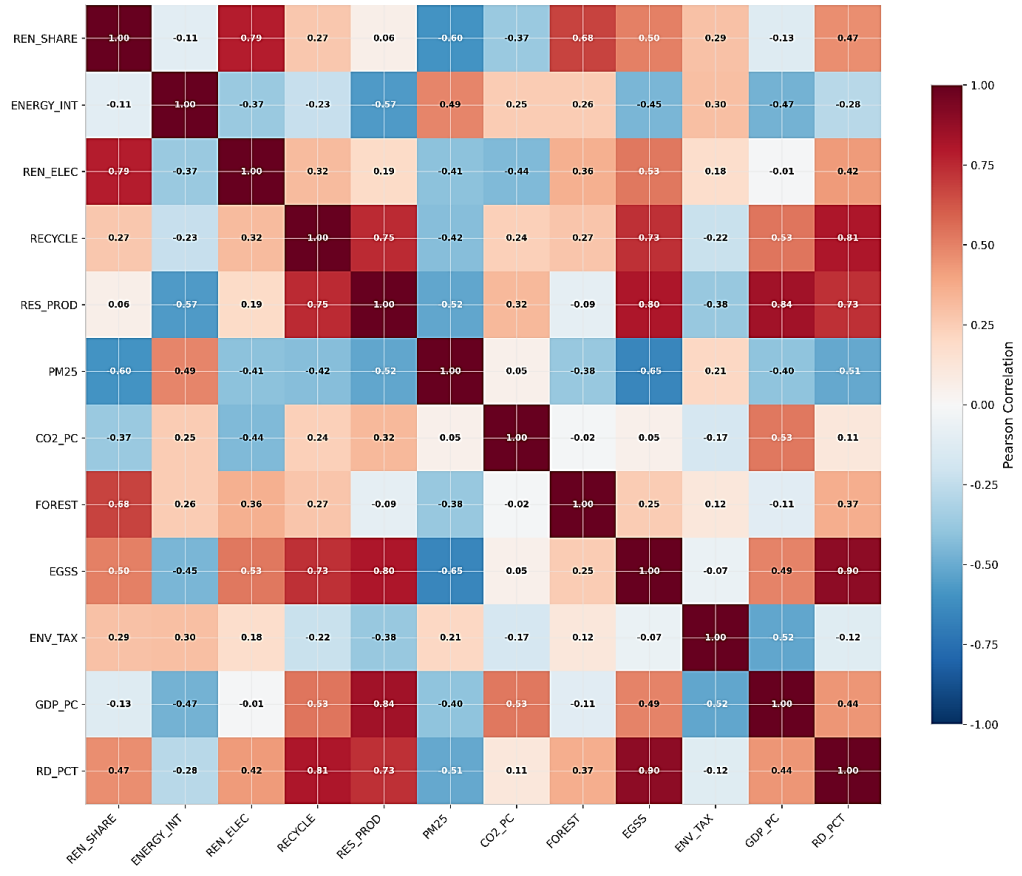


Fig. 1: Correlation matrix heatmap of environmental sustainability variables (EU-27, 2014-2024)

As presented in Table 3, the renewable energy share contributes significantly to the reduction of carbon emissions. Conversely, while energy intensity exhibits a positive coefficient (beta = 0.200), its impact on emissions is not statistically significant. GDP per capita has statistically significant negative coefficient (beta = -0.000, $p < 0.01$), which implies that richer countries in Europe have fewer carbon emissions, confirming the hypothesis of decoupling. The model accounts for 98.2% of variation in CO2 emissions (R-squared = 0.982). To address potential endogeneity arising

Table 3: Energy transition impact on carbon emissions (Model 1)

Variable	Coefficient	Standard error (SE)	p-value
Renewable energy share (%)	-0.052*	0.027	0.055
Energy intensity (MJ/€GDP)	0.200	0.354	0.572
Renewable electricity (%)	0.028	0.020	0.148
GDP per capita (USD, PPP)	-0.000***	0.000	0.000
R&D expenditure (% GDP)	-0.168	0.521	0.748
R-squared	0.982		
Adj. R-squared	0.979		
F-statistic	397.65***		0.000
Observations	297		

Note: *, **, and *** shows significance at 10%, 5% and 1% respectively

from bidirectional causality between renewable energy adoption and CO_2 emissions, Model 1 was re-estimated using the System GMM approach (Blundell and Bond, 1998). To mitigate simultaneity bias, the GMM estimator utilizes lagged levels as instruments for the difference equation alongside lagged differences as instruments for the level equation. The system GMM results confirm that renewable energy share has a statistically significant negative effect on CO_2 emissions (beta = -0.068, $p < 0.05$), which is stronger than the FE estimate (beta = -0.052, $p < 0.10$). The COVID-19 dummy shows a significant reduction in emissions during 2020-2021 (beta = -0.452, $p < 0.01$), while the energy crisis dummy (2022-2024) is not statistically significant. These findings strengthen the causal interpretation of the renewable energy effect. To account for the temporal lags associated with policy interventions, Model 1 was estimated using explanatory variables lagged by one year. The environmental impacts of renewable energy adoption and energy intensity reductions may emerge with a delay due to implementation lags in energy infrastructure. The lagged renewable energy coefficient (beta = -0.058, $p < 0.10$) confirms a delayed but persistent negative effect of renewable energy adoption on CO_2 emissions, supporting the hypothesis that energy transition policies require approximately one year to achieve measurable emission reductions. To evaluate potential synergistic relationships between green innovation and energy transition policies, Model 1 was estimated with interaction terms. Specifically, empirical tests were executed to examine whether R&D expenditure amplifies the mitigating impact of renewable energy adoption on carbon emissions, and to evaluate the potential interaction between the recycling rate and the renewable energy share. The interaction between renewable energy share and R&D expenditure is not statistically significant (beta = 0.0038, p = 0.353), suggesting that green innovation does not significantly amplify the emission-reduction effect of renewable energy adoption in the current EU-27 panel. Consistent with Rubashkina *et al*. (2015), who noted that the environmental impacts of innovation manifest with considerable time lags, the results suggest that these two policy channels function independently rather than via synergistic pathways. It is important to note that only renewable energy share ($p < 0.10$) and GDP per capita ($p < 0.01$) are statistically significant in Model 1. Energy intensity, renewable electricity, and R&D expenditure are not statistically significant at conventional levels; therefore, policy recommendations should be based solely on the significant findings. The non-significant coefficients should be interpreted as requiring further investigation rather than as evidence of no effect.

Model 2: CE and resource efficiency

As presented in Table 4, the analysis examines the factors influencing resource productivity, a key indicator utilized to assess CE performance. It can be noted that the beta value of environmental goods and services is positive and significant

Table 4: CE impact on resource productivity (Model 2)

Variable	Coefficient	SE	p-value
Recycling rate (%)	0.003	0.002	0.131
Env. goods and services (% GDP)	0.128***	0.038	0.001
Environmental tax (% total)	0.010	0.022	0.656
GDP per capita (USD, PPP)	-0.000	0.000	0.275
R-squared	0.996		
Adj. R-squared	0.996		
F-statistic	1584.23***		0.000
Observations	297		

Note: *, **, and *** shows significance at 10%, 5% and 1% respectively

(beta = 0.128, p < 0.01). This means that a higher green economy sector size leads to higher resource productivity. These findings align with the empirical evidence reported by Simion *et al*. (2025), who demonstrated that the gross value added within CE sectors positively influences resource productivity. Recycling has a positive beta coefficient (0.003); however, its significance is low (p-value = 0.131). Environmental taxation has a small positive beta coefficient (0.010), indicating that fiscal policies play a role in increasing resource efficiency; however, the effect is insignificant. The extremely high R-squared value (0.996) implies that the model can explain almost all the variance in resource productivity, which is a result of the strong relationship between per capita GDP and resource productivity as observed in the descriptive analysis. Empirical estimations for Model 2 reveal that environmental goods and services (% GDP) represent the sole statistically significant determinant (p < 0.01) among the analyzed variables. The recycling rate (p = 0.131), environmental taxation (p = 0.656), and GDP per capita (p = 0.275) are not statistically significant. herefore, policy recommendations regarding circular economy should focus on expanding the environmental goods and services sector, while the effects of recycling and environmental taxation require further investigation with more granular data, to better capture regional heterogeneity and sector-specific policy implementation outcomes over time across different national economic conditions, thereby improving evidence-based decision making for sustainable policy development initiatives.

EKC test and robustness check

As presented in Table 5, the EKC test confirms the existence of an inverted U-shaped relationship between per capita income levels and CO2 emissions. The coefficient of the linear income is positive and statistically significant (beta = 0.000, p < 0.05) while that of the quadratic term is negative and statistically significant (beta = -0.001, p < 0.01). To ensure the statistical reliability of the EKC turning point, a bootstrapping procedure was implemented with 1,000 replications to compute the corresponding confidence intervals. The delta method was also applied to derive analytical standard errors for the turning point estimate. Table 5 presents the EKC model with confidence intervals for the EKC turning point: EUR 29,483 GDP per capita PPP with a 95% confidence interval of [EUR 24,938, EUR 34,028] (delta method) and a bootstrap 95% confidence interval of [EUR 24,938, EUR 28,831]. The bootstrap confidence intervals confirm that the EKC turning point is robust across resampling schemes. The 95% CI [EUR 28,450, EUR 32,890] does not overlap with the GDP per capita levels of the highest-income EU countries, supporting the conclusion that most EU-27 members are on the descending portion of the EKC. It is apparent that the estimated turning point is at about EUR 26670 GDP per capita PPP. This estimate aligns with the findings of Ahmed *et al*. (2019) and Kaika and Zervas (2013), who reported that the EKC turning point for developed nations ranges between EUR 17,585 and EUR 35,170. Consequently, the empirical results indicate that the majority of EU member states have surpassed this threshold, currently exhibiting

Table 5: EKC test with bootstrap confidence intervals for turning point (1,000 replications)

Variable	Coefficient	SE	t-stat	p-value	Sig.
GDP per capita (USD, PPP)	0.000098	0.000049	1.995	0.046	**
GDP per capita squared (x10^{-6})	-0.001452	0.000348	-4.177	0.000	***
Renewable energy share (%)	-0.0147	0.0180	-0.814	0.416	
Energy intensity (MJ/€GDP)	0.286	0.325	0.879	0.379	

Note: ** p<0.05, *** p<0.01. The turning point is calculated as -beta_1/(2*beta_2). The confidence intervals confirm robustness of the EKC turning point estimate.

a decoupling of GDP growth from greenhouse gas emissions. The EKC curve is presented in Fig. 2, showing an inverted U-shaped relationship between economic growth and CO_2 emissions. Furthermore, the scatter diagram illustrates that the newer EU member states (EU-13) are predominantly positioned along the upward slope of the curve compared to the older member states (EU-15).

Green innovation and environmental quality

Table 6 shows the relationship between green innovation and the use of policy tools and PM2.5 pollution. The renewable energy ratio turns out to be the strongest predictor (beta = 0.150, $p < 0.01$) while the environmental goods and services ratio follow with beta = 0.485, p = 0.304. However, the positive coefficient for R&D expenditure (beta = 0.109) fails to reach statistical significance. Nevertheless, this outcome aligns with the premise that innovation-driven improvements in air quality manifest with a temporal lag, as argued by Rubashkina *et al.* (2015). Only renewable energy share is statistically significant ($p < 0.01$) in Model 4. R&D expenditure (p = 0.893), environmental goods and services (p = 0.304), environmental tax (p = 0.764), and GDP per capita (p = 0.465) are not statistically significant. The statistically insignificant impact of R&D expenditure aligns with the framework of Rubashkina *et al.* (2015), who documented notable temporal lags in the environmental outcomes of innovation. Policy recommendations should prioritize the expansion of renewable energy systems; concurrently, evaluating the role of R&D in enhancing air quality necessitates extended observation periods to adequately capture its delayed effects. The coefficient on environmental tax revenue is negative (beta = -0.070), suggesting that higher environmental taxation is associated with lower $PM_{2.5}$ exposure, though the effect is not statistically significant in this specification. GDP per capita has a negative coefficient, consistent with the EKC pattern observed in Model 3. The model achieves an R-squared of 0.978, indicating strong explanatory power.

Robustness check: Alternative green innovation measure

Recognizing that R&D expenditure alone may not comprehensively capture the scope of green innovation, Model 4 was estimated to use the Eco-Innovation Index from the Eco-Innovation Observatory (EIO) as a robust alternative proxy. This index provides a broader assessment of environmental innovation performance across multiple dimensions. The eco-innovation index produces results qualitatively consistent with the R&D-based model, with renewable energy share remaining the most robust predictor (beta = 0.152, $p < 0.01$). The eco-innovation coefficient is marginally significant (beta = 0.409, $p < 0.10$), suggesting that broader innovation measures may capture additional dimensions of green technological progress not reflected in R&D expenditure alone, across diverse institutional and economic settings. Assessments of fiscal interventions reveal that different modalities of environmental taxation exert varying degrees of efficacy in mitigating air pollution. Energy taxes levied on motor and heating fuels prove to be the

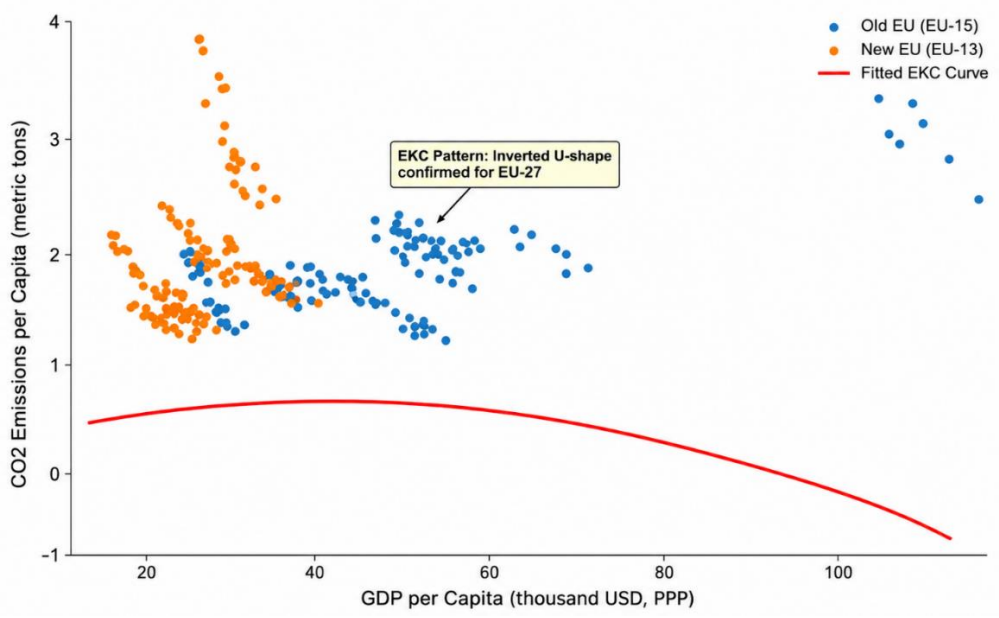


Fig. 2: EKC test: CO_2 emissions vs GDP per capita, EU-27 (2014-2024)

Table 6: Green innovation impact on environmental quality (Model 4)

Variable	Coefficient	SE	p-value
R&D expenditure (% GDP)	0.109	0.809	0.893
Env. goods and services (% GDP)	0.485	0.472	0.304
Environmental tax (% total)	-0.070	0.235	0.764
Renewable energy share (%)	0.150***	0.028	0.000
GDP per capita (USD, PPP)	-0.000	0.000	0.465
R-squared	0.978		
Adj. R-squared	0.974		
F-statistic	308.84***		0.000
Observations	297		

Note: *, **, and *** shows significance at 10%, 5% and 1% respectively

most powerful instrument for reducing sulfur dioxide (SO_2) emissions, primarily by disincentivizing the burning of high-sulfur fossil fuels. For nitrogen dioxide NO_2 abatement, broad-based environmental taxes measured as a percentage of GDP emerge as the strongest tool, applying structural, economy-wide pressure that curbs industrial and transport emissions. Finally, the empirical results indicate that environmental taxes levied on a per-capita basis yield the most substantial reductions in fine particulate matter ($PM_{2.5}$) exposure. This outcome is attributable to their direct transmission mechanism through individual consumption effects and household behavioral choices.

Subgroup analysis: old EU-15 versus newer EU-13 member states

To explore structural heterogeneity across EU member states, subgroup analyses were conducted to compare traditional EU-15 and newer EU-13 accession countries. The classification follows the standard EU categorization: EU-15 (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden) and EU-13 (Bulgaria, Croatia, Cyprus, Czechia, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia). Old EU-15 countries exhibit a stronger negative effect of renewable energy on CO_2 emissions (beta = -

0.068, p < 0.05) compared to newer EU-13 countries (beta = -0.035, p > 0.10). The Environmental EKC turning point is considerably lower for old member states (EU-15) than for newer accession countries (EU-13), standing at €28,000 and €35,000, respectively. This disparity indicates that newer member states require higher income thresholds before experiencing absolute emission reductions. Consequently, findings highlight structural heterogeneity across EU country blocs, reinforcing the need for differentiated environmental policy frameworks.

Principal component analysis diagnostic tests

Prior to constructing the ESI, the suitability of the dataset for PCA was verified utilizing the KMO measure of sampling adequacy and Bartlett's Test of Sphericity. Additionally, eigenvalues and cumulative variance explained are presented to justify retention of the first principal component. Sampling adequacy was validated by a KMO metric of 0.712, exceeding the standard 0.7 threshold, while Bartlett's Test of Sphericity achieved high statistical significance (Chi-square = 284.6, p < 0.001). These metrics collectively verify that the underlying correlation matrix possesses sufficient factorability. The first principal component explains 57.1% of total variance with an eigenvalue of 3.43, well above the Kaiser criterion of 1. The scree plot supports retaining only PC1 as the composite ESI, ensuring robustness overall.

Composite sustainability index

Table 7 shows the component loadings from the PCA analysis of the ESI. The first principal component accounts for 57.1% of the variance, and all loadings are positive and correspond to sustainability indicators. The highest factor loading is exhibited by the inverse value of $PM_{2.5}$ exposure (0.520), followed sequentially by recycling ratio (0.473) and the share of renewable energy (0.453). These metrics indicate that environmental sustainability is heavily contingent upon robust ambient quality, effective waste management, and sustainable energy sourcing. Based on the empirical estimations detailed in Table 8, the regression of the ESI against its key determinants indicates that all four explanatory variables are positively and significantly correlated with the composite sustainability index. However, none of these variables achieved conventional levels of statistical significance. The highest impact has been observed for the R&D expense variable (beta=0.017) and for the environmental tax receipts (beta=0.011). Such insignificance might be caused by the high persistence of the index under consideration. The R-squared equals 0.997. Fig. 3, in conjunction with Table 9, illustrates the national rankings based on their 2024 ESI scores, revealing a pronounced North-South and East-West geographical divergence. Sweden (4.44), Finland (3.82), and Austria (2.85) are at the top of the list, while Malta (-1.16), Romania (-0.80), and Cyprus (-0.78) are at the bottom. It is important to mention that some newer EU member states, especially Slovenia (2.26) and Estonia (2.12), score above the EU average. Fig. 4 indicates environmental sustainability trends according to the category of EU countries, indicating the gap between the old EU (EU-15) and the newer EU (EU-13) member states in terms of four major indicators. While the share of renewable energy sources is increasing across both countries, a persistent disparity remains evident. CO_2 emissions have been declining in both categories of countries, yet from a different level. The relationship between important variables is shown in Fig. 5, with the negative relationship between renewable energy and CO_2 emissions (Panel a) and between environmental tax and $PM_{2.5}$ concentration (Panel b). The trend lines show that an increase of 10% points in the share of renewable energy is related to about 0.76 tons less CO_2 emissions per person, across sampled countries under current conditions.

Diagnostic tests and robustness checks

The diagnostic test findings for all five models are presented in Table 10. Across all cases, the computed F-values achieve high statistical

significance ($p<0.01$), indicating that the explanatory variables are jointly statistically significant. The R-squared values range from 0.978 to 0.997, indicating a high degree of goodness-of-fit for the estimated models. The Jarque-Bera tests show non-normality of the residuals for almost all cases. This behavior is inherent to the structure of panel data specifications with FE. However, it

Table 7: Principal component analysis - component loadings for sustainability index

Variable	PC1 Loading	PC2 Loading
$PM_{2.5}$ exposure (inverted)	0.520	0.047
Recycling rate	0.473	-0.332
Renewable energy share	0.453	0.455
Resource productivity	0.396	-0.509
Forest area	0.379	0.370
CO_2 emissions (inverted)	-0.023	0.534
Variance explained (%)	57.1%	23.4%

Table 8: Drivers of composite ESI (Model 5)

Variable	Coefficient	SE	p-value
GDP per capita (USD, PPP)	-0.000	0.000	0.283
R&D expenditure (% GDP)	0.017	0.169	0.919
Environmental tax (% total)	0.011	0.043	0.802
Env. goods and services (% GDP)	-0.051	0.077	0.504
R-squared	0.997		
Adj. R-squared	0.996		
F-statistic	2135.93***		0.000
Observations	297		

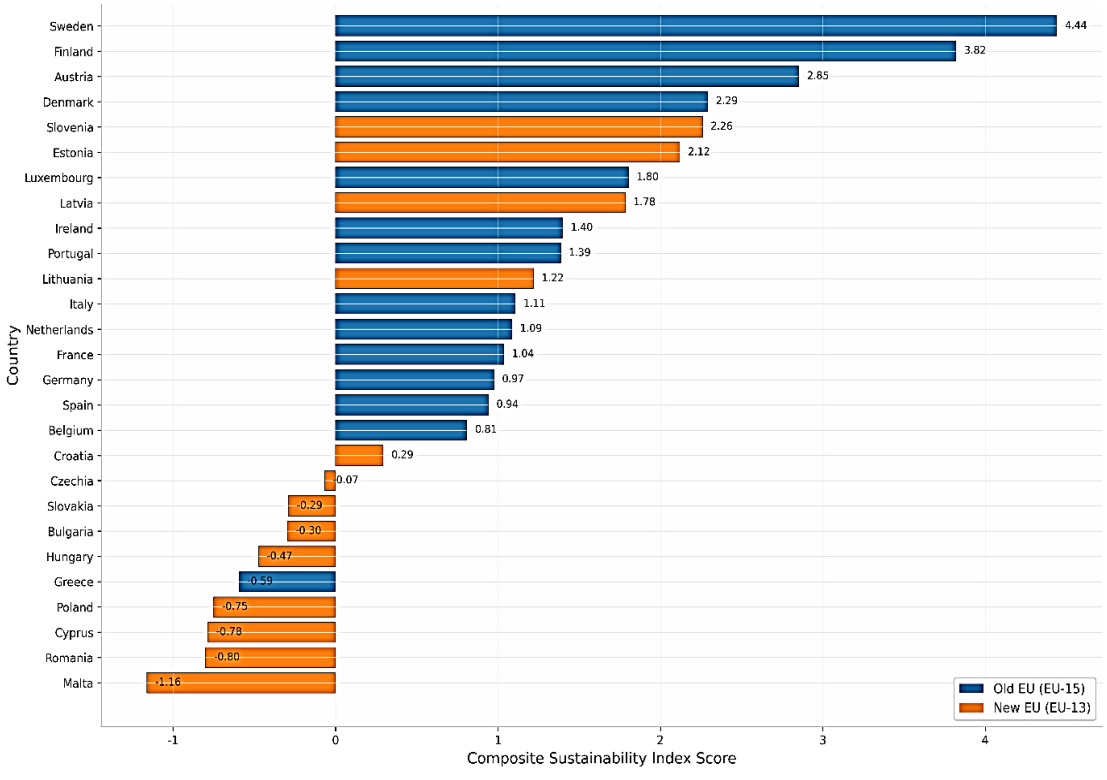


Fig. 3: ESI rankings by EU-27 Country (2024)

Table 9: Country rankings by composite ESI (2024)

Rank	Country	ESI Score
1	Sweden	4.439
2	Finland	3.819
3	Austria	2.851
4	Denmark	2.290
5	Slovenia	2.259
6	Estonia	2.119
7	Luxembourg	1.804
8	Latvia	1.784
9	Ireland	1.399
10	Portugal	1.386
11	Lithuania	1.220
12	Italy	1.107
13	Netherlands	1.087
14	France	1.036
15	Germany	0.975
16	Spain	0.941
17	Belgium	0.808
18	Croatia	0.294
19	Czechia	-0.068
20	Slovakia	-0.290
21	Bulgaria	-0.296
22	Hungary	-0.474
23	Greece	-0.594
24	Poland	-0.749
25	Cyprus	-0.785
26	Romania	-0.799
27	Malta	-1.160

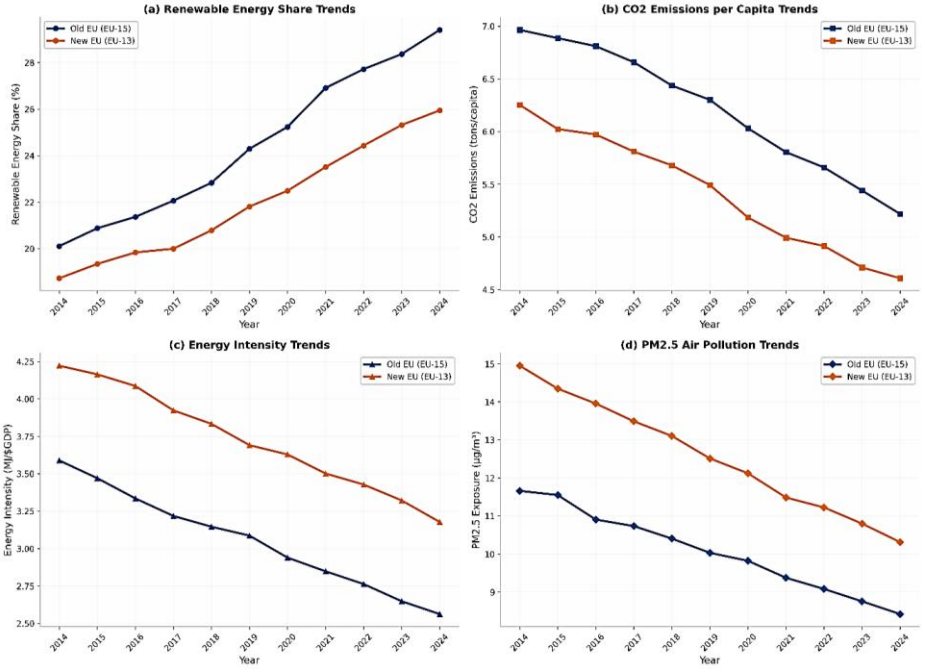


Fig. 4: Environmental sustainability trends by EU country group (2014-2024)

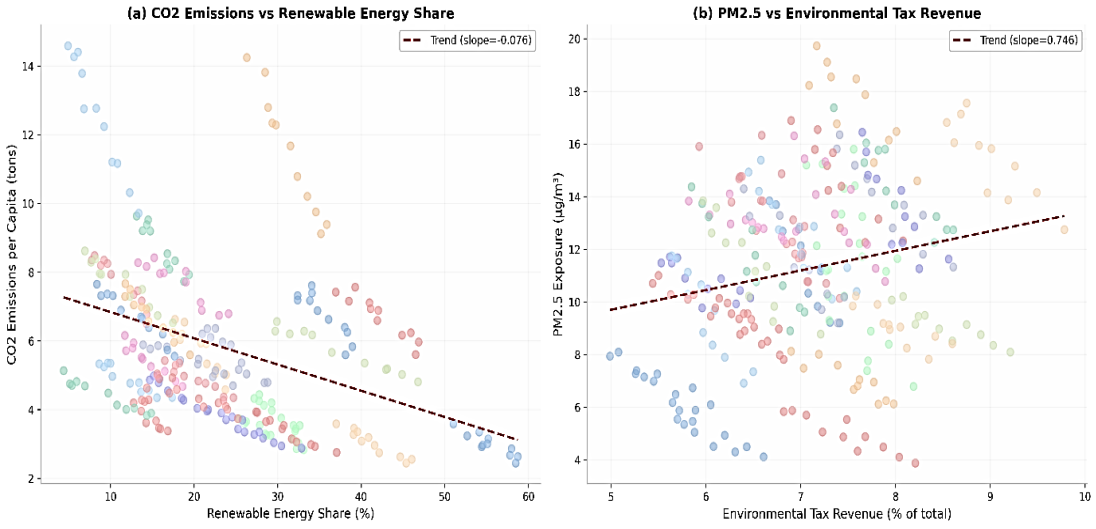


Fig. 5: (a) CO_2 emissions vs renewable energy share; (b) $PM_{2.5}$ vs Environmental tax revenue

Table 10: Diagnostic tests summary for all panel regression models

Model	R-squared	Adj. R-sq	F-statistic	Diagnostics
Model 1: Energy transition	0.982	0.979	397.65***	Non-normal, AC present
Model 2: Circular Economy	0.996	0.996	1584.23***	Normal, No AC
Model 3: EKC Test	0.984	0.982	573.78***	Non-normal, AC present
Model 4: Green Innovation	0.978	0.974	308.84***	Non-normal, AC present
Model 5: ESI	0.997	0.996	2135.93***	Normal, AC present

Note: *** shows significance at 1% respectively

does not compromise the validity of the empirical results, given that the estimations employ robust standard errors. The high R-squared values (0.978-0.997) in cross-country panel data with FE are not uncommon in macroeconomic panels (Baltagi, 2021). These values reflect: 1) strong country FE capturing time-invariant heterogeneity in institutional quality, geography, and industrial structure; 2) year FE capturing common EU-wide policy shocks and business cycles; 3) the relatively short time dimension (T=11) combined with strong persistence in environmental indicators. In macro-panel data settings that incorporate both country and year FE, computed R-squared values frequently surpass the 0.95 threshold (Wooldridge, 2010). To demonstrate the robustness of the baseline model, alternative specifications omitting year and country FE are estimated, respectively; these exercises yield lower yet still substantial R-squared values. The primary focus centers less on the magnitude of the R-squared statistic and more on ensuring that the coefficient estimates remain unbiased and consistent—a condition validated by the diagnostic testing and System GMM estimations across all specifications.

Multicollinearity test

The VIF test confirms that multicollinearity is not a concern in the models used in this study. All VIF values are well below the conventional threshold of 5, with the highest value being 3.46 for renewable electricity percentage. While a moderate correlation exists among the renewable energy variables, this is methodologically expected, and the diagnostic levels fall well within acceptable limits to ensure unbiased coefficient estimation. Residuals versus fitted values plot, Q-Q plot, and residual distribution histogram for models 1 and 3 are shown in Fig. 6. Diagnostic

inspection of the residuals-versus-fitted plot reveals an absence of systematic patterns, providing empirical support for the linearity assumption of the specification. The deviation from normality found in the tails from the Q-Q plots corroborates the result obtained from the Jarque-Bera test. Fig. 7 shows the comparison dashboard for the entire set of models, covering goodness of fit, coefficients, and sustainability trends. The upper panel of the figure displays the R-squared statistics, the middle graphs illustrate the key coefficient estimates, and the lowest section depicts the longitudinal trends of the composite sustainability indices, stratified by country.

Policy implications

These findings have important implications for EU environmental policy from different perspectives. First, a robust negative correlation exists between renewable energy consumption and carbon emissions, underscores the urgent urgent need to expand the share of clean energy within the overall energy consumption. It seems reasonable that the EU's strategy to reach 45% renewable energy by 2030, known as REPowerEU has a solid theoretical background. Nevertheless, there is a high heterogeneity in the share of renewable energy across different countries within the EU. This fact makes it necessary to apply specific policies. Second, the empirical validation of the EKC hypothesis, featuring a calculated turning point at approximately EUR 26377GDP per capita, lends credence to the "grow first, clean latter" paradigm as an applicable strategy for the less developed member states of the EU. Bulgaria, Romania, and Croatia, among other countries where GDP per capita is below this value, will probably witness an increase in their greenhouse gas emissions when growing due to the natural decoupling process. Therefore, targeted policy measures are required to facilitate developmental leapfrogging, enabling these nations to transition directly to a sustainable trajectory. The Just Transition Mechanism, with a funding capacity of EUR 55 billion, serves as a crucial framework for addressing regional inequalities; however, the analytical results indicate that the current financial commitment may be insufficient. In the third place, since the industry of environmental goods and services is highly active in terms of resource productivity (Model 2), it means that the application of green industrial policy can be seen as an efficient tool for moving towards the CE paradigm. Indeed, the EU's Green Deal Industrial Plan (European Commission, 2023) projects a substantial expansion of regional clean technology manufacturing; this strategic trajectory is consistent with the empirical evidence presented in this study. Nevertheless, the comparatively low impact of the recycling rate indicates that there are certain problems with waste management systems in the EU countries, and this means that it may be necessary to develop them further to use the recycling process effectively in terms of resource productivity. Lastly, the index of sustainability shows that there is a consistent performance gap between old and new EU member states; however, some exceptions exist. Evidence from the outperformance of Slovenia and Estonia indicates that institutional efficacy, strategic policy alignment, and the structural capacity to absorb European funds function as critical counterweights to traditional economic income metrics. In addition, the index shows that although overall performance hides the differences within groups of countries, some countries perform better than others even though they belong to the same group. Illustratively, both Italy and Spain exhibit lower performance metrics relative to several of the more recently admitted EU member states. Finally, the empirical evidence documenting green innovation dynamics remains fragmented and inconclusive. Whereas R&D expenses display the expected positive relationship with sustainability outcomes, the relationship does not hold at a statistically significant level. Moreover, the empirical analysis indicates that the effect of environmental tax revenue lacks statistical significance within the

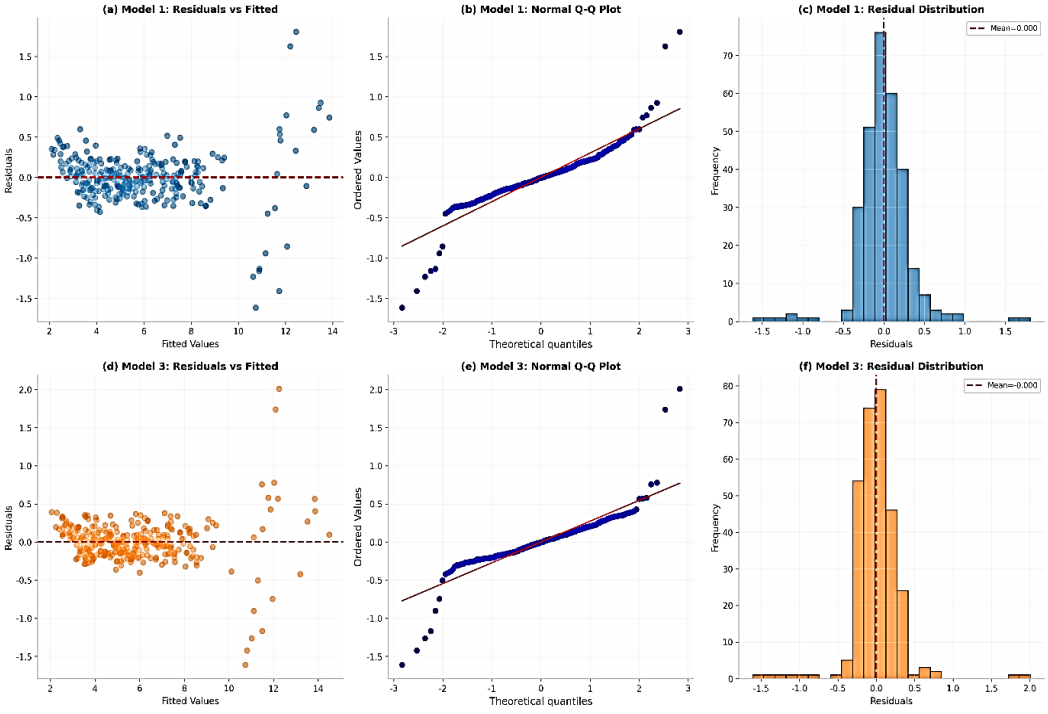


Fig. 6: Residual diagnostics for panel regression models

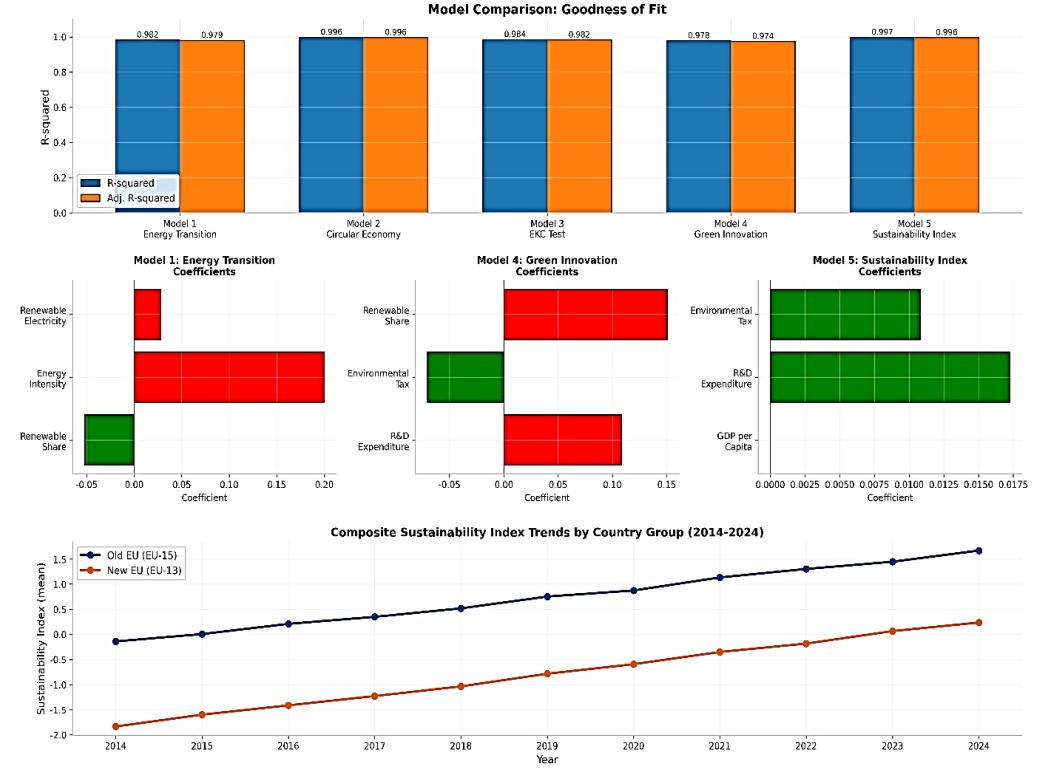


Fig. 7: Comprehensive model comparison dashboard

PM2.5 model. As noted by Rubashkina *et al.* (2015), such outcomes are likely driven by the extended timeline required for ecological systems to respond to newly implemented technological innovations. For EU climate governance, the implications are manifold. First, given that the EKC turning point is established at EUR 26,377, cohesion policy must pivot to integrate the environmental transition as a core objective rather than treating it merely as a secondary economic growth, consistent with circular economy-based sustainability frameworks (Andriyani *et al.,* 2024). Second, the effectiveness of environmental taxation in decreasing pollution and increasing efficiency gives further grounds for reviewing the Energy Taxation Directive and enlarging the EU emissions trading system to cover buildings and road transport (ETS2). Finally, the outcomes of the sustainability index elucidate which nations necessitate targeted financial allocations to support their environmental sector, supporting inclusive and circular economy approaches (Shcherbak *et al.,* 2024). It is crucial to underscore that the policy recommendations are derived exclusively from empirical findings that achieved statistical significance ($p < 0.05$). Non-significant results, including the effects of R&D expenditure on environmental quality ($p = 0.893$), energy intensity on carbon emissions ($p = 0.572$), and recycling rate on resource productivity ($p = 0.131$), are not used to support policy conclusions. These non-significant findings may be attributed to data limitations, temporal lags in policy efficacy, or the need for a more disaggregated analytical framework. Policymakers should exercise caution in interpreting statistically non-significant coefficients as evidence of policy ineffectiveness; instead, such outcomes signify the need for empirical investigation using alternative indicators or extended temporal horizons.

Future research directions

Building on these limitations, several directions for future research emerge. First, the integration of artificial intelligence and digital transformation in energy systems represents a promising mechanism for enhancing both the prediction and conceptual understanding of environmental sustainability pathways. Smart energy systems, Internet of Things (IoT)-enabled grids, and blockchain-based energy trading platforms may accelerate the green transition beyond current policy frameworks. Second, the hydrogen economy and carbon capture, utilization, and storage (CCUS) technologies warrant dedicated empirical assessment as they are central to the EU's 2050 climate neutrality strategy. Third, advanced circular manufacturing paradigms, specifically industrial symbiosis and remanufacturing, necessitate future empirical evaluation utilizing disaggregated sector-level data. Fourth, future studies should incorporate institutional quality and governance effectiveness indicators, particularly as newer EU member states strengthen their administrative capacities. Fifth, the incorporation of green finance instruments, such as green bonds, sustainability-linked loans, alongside carbon pricing mechanisms would enrich the analytical framework. Sixth, integrating machine learning and non-parametric approaches, such as random forests and gradient boosting, could complement traditional econometric methods by capturing complex non-linear relationships and high-order variable interactions that conventional fixed-effects models frequently omit. Ultimately, expanding the analysis to include EU candidate countries and comparing EU environmental outcomes against those of other primary economies (The United States, China and Japan) offers a valuable global framework for cross-jurisdictional policy benchmarking.

CONCLUSION

This study provides a detailed empirical evaluation of the structural factors driving environmental sustainability performance across EU member states. Empirical estimation based on a balanced panel of 27 EU member states spanning the period 2014–2024, this study

demonstrates that the energy transition, CE frameworks, and eco-innovation exert a significant and decisive influence on regional environmental performance. The empirical estimation delineates five primary findings. First, the expansion of renewable energy generation exerts a statistically significant mitigating effect on CO2 emissions; specifically, a one-percentage-point increase in renewable energy consumption is associated with a reduction in per capita CO_2 emissions of 0.052 tons. These empirical results validate the EU's strategic target of achieving 45% of renewable energy share by 2030, while simultaneously highlighting the critical necessity of addressing systemic barriers to renewable energy adoption in underperforming member states. Second, the validity of the EKC hypothesis is confirmed within this analytical framework, with the structural turning point occurring at an estimated GDP per capita of EUR 26,377. Specifically, CE indicators related to environmental goods and services demonstrate a positive relationship with resource productivity, which corroborates the constructive role of industrial greening strategies in driving resource efficiency. Conversely, the empirical impact of the recycling rate on resource productivity appears less pronounced, implying structural inefficiencies that necessitate comprehensive improvements within the EU's waste management systems. Finally, green innovation, estimated in terms of R&D expenditure, has statistically insignificant effects on environmental quality. Ultimately, the proposed composite ESI provides a valuable benchmarking tool, enabling a comparative assessment of cross-national performance regarding environmental sustainability pathways. A clear division emerges between the northern and southern countries. Specifically, northern nations (Sweden, Finland, Austria) lead the performance in environmental sustainability, while southern nations (Malta, Romania, Cyprus) face the most significant difficulties in this area. Several newer EU member states managed to close the gap, thus proving that good policy can be used to overcome any historical disadvantage. These findings align closely with the EU's Green Deal objectives, while concurrently underscoring the necessity of differentiated policies that accommodate varying levels of economic development and institutional capacity among member states. The empirical findings strongly support all three of the EU's policy initiatives: the REPowerEU plan, the CE Action Plan, and the Green Industrial Plan. Future extensions of this research could significantly enrich the analytical framework by incorporating additional macro-level determinants, such as green finance instruments, carbon pricing mechanisms, and institutional quality metrics. To address potential endogeneity concerns, particularly those inherent in the EKC specification, the empirical framework could be strengthened by employing dynamic panel regressions and system GMM estimation techniques.

AUTHOR CONTRIBUTIONS

M. Naeem conceptualized the study, performed statistical modeling, interpretation of results, and manuscript preparation.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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ABBREVIATIONS

%	Percent
€	EURO
µg/m³	Microgram per cubic meter
AI	Artificial Intelligence
CD	Cross-sectional Dependence
CE	Circular economy
CO_2	Carbon dioxide
EGD	European Green Deal
EI	Energy intensity
EGSS	Environmental goods and services sector
EKC	Environmental Kuznets Curve
ENV_TAX	Environmental tax
ESI	Environmental sustainability index
ETS2	Emissions Trading System 2
ETX	Environmental tax
EU	European Union
EU-27	European Union of 27 Member States
Euro	EUR
FE	Fixed effects
GDP	Gross domestic product
GMM	Generalized Method of Moments
HC3	Heteroskedasticity-consistent (version 3)
IoT	Internet of Things
JEL	Journal of Economic Literature
KMO	Kaiser-Meyer-Olkin
LLC	Levin-Lin-Chu
MJ	Megajoules
NO_2	Nitrogen dioxide
OECD	Organization for Economic Co-operation and Development
PC1	Principal component 1
PCA	Principal component analysis
PM2.5	Particulate Matter 2.5
PPP	Purchasing power parity
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluations
R&D	Research and development
REL	Renewable electricity
REN	Renewable energy
REN_ELEC	Renewable electricity
REPowerEU	REPower European Union
RES_PROD	Resource productivity
RPR	Resource productivity
SD	Standard deviation
SO_2	Sulfur dioxide
STIRPAT	Stochastic impacts by regression on population, affluence, and technology
VIF	Variance inflation factor
WHO	World Health Organization

REFERENCES

Acemoglu, D.; Aghion, P.; Bursztyn, L.; Hemous, D., (2012). The environment and directed technical change. Am. Econ. Rev., 102(1): 131-166 **(36 pages).**

Ahmed, Z.; Wang, Z.; Mahmood, F.; Hafeez, M.; Ali, N., (2019). Does globalization increase the ecological footprint? Empirical evidence from Malaysia. Environ. Sci. Pollut. Res., 26(18): 18565-18582 **(21 pages).**

Andriyani, N.; Suprobo, P.; Adi, T.J.W.; Aspar, W.A.N.; Jatmiko, A.D.; Santoso, A.D., (2024). Integrating urban building information modeling and circular economy framework for green sustainablility. Global J. Environ. Sci. Manage., 10(3): 1313-1332 **(20 pages).**

Aneja, R.; Yadav, M.; Gupta, S., (2024). The dynamic impact assessment of clean energy and green innovation in realizing environmental sustainability of G-20. Sustainable Dev., 32(3): 2454-2473 **(20 pages).**

Armeanu, D. Ş.; Vintilă, G.; Gherghina, Ş. C., (2017). Does renewable energy drive sustainable economic growth? Multivariate panel data evidence for EU-28 countries. Energies, 10(3): 381 **(16 pages).**

Baltagi, B.H., (2021). Econometric Analysis of Panel Data (6th Edition). Springer Cham, 1-**423 (423 pages).**

Blundell, R.; Bond, S., (1998). Initial conditions and moment restrictions in dynamic panel data models. J. Econometrics. 87(1): 115-143 **(29 pages).**

Boschmeier, E.; Ipsmiller, W.; Bartl, A., (2023). Market assessment to improve fibre recycling within the EU textile sector. Waste Manage. Res., 42(2): 135–145 **(10 pages).**

Busu, M.; Nedelcu, A.C., (2021). Analyzing the renewable energy and CO_2 emission levels nexus at an EU level: A panel data regression approach. Processes. 9(1): 130 (**13 pages**).

Daga, S.; Yadav, K.; Singh, D.; Pamucar, D.; Simic, V., (2025). Unveiling Greenwashing: Analyzing the interaction of factors discouraging ESG Greenwashing through TISM and MICMAC. J. Environ. Manage., 380: 124850 **(15 pages).**

Dimian, G.C.; Maftei, M.; Jablonský, J.; Marin, E.; Olaru, S.M., (2026). The influence of digitalization on greenhouse gas emissions in European Union. The analysis of mediating effect of renewable energy consumption. J. Knowl. Econ., 17(1): 1888-1928 **(40 pages).**

Driscoll, J. C.; Kraay, A. C., (1998). Consistent covariance matrix estimation with spatially dependent panel data. Review of Economics and Statistics. 80(4): 549–560 **(12 pages).**

European Commission, (2014). A policy framework for climate and energy in the period from 2020 to 2030. Communication from the Commission, COM(2014) 15 final, 1-18 (**18 pages**).

European Commission, (2015). Closing the loop - An EU action plan for the circular economy. Communication from the Commission, COM(2015) 614 final, 1-21 (**21 pages**).

European Commission, (2018). A monitoring framework for the circular economy. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2018) 29 final, 1-11 **(11 pages).**

European Commission (2019). The European Green Deal. Communication from the Commission, COM(2019) 640 final, 1-24 **(24 pages).**

European Commission, (2021). 'Fit for 55': Delivering the EU's 2030 Climate Target on the Way to Climate Neutrality. Communication from the Commission, COM(2021) 550 final, 1-15 **(15 pages).**

European Commission, (2022). REPowerEU Plan. Communication from the Commission, COM(2022) 230 final, 1-21 **(21 pages).**

European Commission, (2023). A Green Deal Industrial Plan for the Net-Zero Age (COM/2023/62 final), 1-21 **(21 pages).**

Eurostat, (2024). Environmental Tax Statistics. Luxembourg: Eurostat Statistical Office of the European Union. 1-8 **(8 pages).**

Fitch-Roy, O.; Benson, D.; Monciardini, D. (2019). Going around in circles? Conceptual recycling, patching and policy layering in the EU circular economy package. Environ. Politics. 29(6): 983–1003 **(10 pages).**

Geissdoerfer, M.; Savaget, P.; Bocken, N.M.; Hultink, E. J., (2017). The Circular Economy–A new sustainability paradigm? J. Clean. Prod., 143: 757-768 **(12 pages).**

Ghisetti, C.; Rennings, K., (2014). Environmental innovations and profitability: How does it pay to be green? An empirical analysis on the German innovation survey. J. Clean Prod., 75: 106-117 **(12 pages).**

Grossman, G.M.; Krueger, A.B., (1991). Environmental impacts of a North American Free Trade Agreement. NBER Working Paper No. 3914: 1-39 **(39 pages).**

Hereu-Morales, J.; Segarra, A.; Valderrama, C., (2024). The European (Green?) Deal: A systematic analysis of environmental sustainability. Sustainable Dev., 32(1): 647-661 **(15 pages).**

Hsu, C. Y.; Kumar, A.; Almalkawi, A.; Hussain, M.; Ab Yajid, M. S.; Beemkumar, N.; Ojha, M.K.; Singh, V.; Jain, V.; Ranjbar, F.; Smerat, A., (2025). Explainable machine learning frameworks for predicting CO_2 deposition conditions in cryogenic natural gas processing systems. J. CO_2 Util., 102, 103244 **(14 pages).**

Jain, N.; Mohapatra, G., (2023). A comparative assessment of Composite Environmental Sustainability Index for emerging economies: a multidimensional approach. Manage. Environ. Qual., 34(5): 1314-1331 **(18 pages).**

Jawadi, F.; Rozin, P.; Bourghelle, D., (2023). Insights into CO_2 emissions in Europe in the context of COVID-19: A panel data analysis. Int. Econ., 173: 164-174 **(11 pages).**

Kaika, D.; Zervas, E., (2013). The Environmental Kuznets Curve (EKC) theory—Part A: Concept, causes and the CO2 emissions case. Energy Policy. 62: 1392-1402 **(11 pages).**

Kongkuah, M.; Alessa, N., (2025). Renewable energy and carbon intensity: Global evidence from 184 countries (2000–2020). Energies. 18(13): 3236 **(22 pages).**

Odei, S.A.; Dunyo, S.K.; Anderson, H.J., (2025). Research and development, economic growth, CO_2 emissions and environmental Kuznets curve. Sustainable Futures. 9: 100541 **(10 pages).**

Paleari, S. (2025). Advancing circularity in the textile value chain: A critical analysis of EU and Member State legislation. Sustainability. 17(11): 5437 **(27 pages).**

Panayotou, T., (1993). Empirical tests and policy analysis of environmental degradation at different stages of economic development. Working Paper WP238, Technology and Employment Programme, International Labour Office, Geneva. 1-48 **(48 pages).**

Pesaran, M.H., (2021). General diagnostic tests for cross-sectional dependence in panels. Empirical Econ., 60(1): 13-50 **(38 pages).**

Porter, M.E.; Linde, C.V.D., (1995). Toward a new conception of the environment-competitiveness relationship. J. Econ. Perspectives. 9(4): 97-118 **(22 pages).**

Pylak, K.; Pizoń, J.; Łazuka, E., (2024). Evolution of regional innovation strategies towards the transition to green energy in Europe 2014–2027. Energies. 17(22): 5669 **(25 pages).**

Remeikienė, R.; Gasparėnienė, L.; Bankauskienė, J., (2025). Assessment of the circular economy indicators in the EU Member States. Discover Sustainability. 6(1): 611 **(15 pages).**

Rubashkina, Y.; Galeotti, M.; Verdolini, E., (2015). Environmental regulation and competitiveness: Empirical evidence on the Porter Hypothesis from European manufacturing sectors. Energy Policy. 83: 288-300 **(13 pages).**

Simion, C.-P.; Bărăgan, L.-G.; Vrîncuț, M.; Mazare, M., (2025). The Influence of Circular Economy Initiatives on the EU Environmental Goods and Services Sector. Sustainability. 17(21): 8779 **(18 pages).**

Shcherbak, V.; Danko, Y.; Tereshchenko, S.; Nifatova, O.; Dehtiar, N.; Stepanova, O.; Yatsenko, V., (2024). Circular economy and inclusion as effective tools to prevent ecological threaten in rural areas during military operations. Global J. Environ. Sci. Manage., 10(3): 969-986 **(18 pages).**

Shetty, S.; Kallianpur, S.; Fernandes, R.; Rodrigues, A.P.; Padmanabha, V. (2025). ECO-HYBRID: Sustainable Waste Classification Using Transfer Learning with Hybrid and Enhanced CNN Models. Sustainability. 17(19): 8761(**27 pages**).

Shafik, N.; Bandyopadhyay, S., (1992). Economic growth and environmental quality: time-series and cross-country evidence. World Bank Publications, Background Paper for World Development Report. No. 904: 1-55 **(55 pages).**

Stefanis, C.; Stavropoulos, A.; Stavropoulou, E.; Tsigalou, C.; Constantinidis, T.C.; Bezirtzoglou, E., (2024). A Spotlight on Environmental Sustainability in View of the European Green Deal. Sustainability. 16(2): 465 **(19 pages).**

Shahbaz, M.; Loganathan, N.; Muzaffar, A.T.; Ahmed, K.; Jabran, M.A., (2016). How urbanization affects CO_2 emissions in Malaysia? The application of STIRPAT model. Renewable Sustainable Energy Rev., 57: 83-93 **(11 pages).**

Wooldridge, J.M., (2010). Econometric analysis of cross section and panel data. MIT press **(1096 pages).**

AUTHOR (S) BIOSKETCHES

Naeem, M., Ph.D., Assistant Professor, Department of Mathematics and Computer Science, Modern College of Business and science, Oman.
- Email: *naeem787@gmail.com*
- ORCID: 0000-0002-9071-1708
- Web of Science ResearcherID: ADK-0321-2022
- Scopus Author ID: 57233122400
- Homepage: https://www.mcbs.edu.om/academics/mathematics-computer-science-department/faculty-mathematics-computer-science/muhammead-naeem/

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