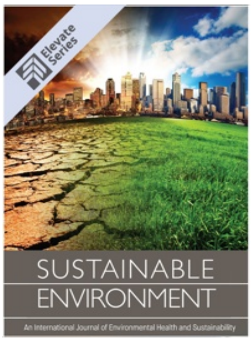

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Navigating the trade-offs between economic growth and environmental sustainability: A global analysis of long-term trends and strategic policies

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ABSTRACT

The complex relationship between economic growth and environmental sustainability remains one of the most pressing global challenges in the context of climate change. This study offers a comprehensive analysis of these trade-offs by leveraging a dynamic panel dataset spanning 170 countries from 2000 to 2020. Using advanced econometric methods, including dynamic panel data models and clustering techniques, this research rigorously tests the Environmental Kuznets Curve hypothesis while exploring the persistence of CO_2 emissions and the role of renewable energy in mitigating environmental damage. The key findings indicate that a 1% increase in GDP leads to a 0.42% rise in CO_2 emissions, highlighting the entrenched environmental costs of growth, particularly in developing and emerging economies. While renewable energy consumption is negatively correlated with emissions, it has yet to achieve the scale required to significantly offset this growth. Cluster analysis uncovers distinct sustainability profiles, revealing that high-GDP economies continue to face challenges in decoupling growth from emissions, while low-GDP countries show smaller carbon footprints but struggle with scaling renewable technologies. These insights demand differentiated policy strategies: advanced economies must accelerate decarbonization and clean energy innovation, while developing nations should prioritize leapfrogging to renewable technologies with international support. This study contributes to the global debate on sustainability by providing actionable policy recommendations aligned with the Paris Agreement, emphasizing the need for stronger international financial flows to assist low-income countries in achieving sustainable development.

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Introduction

In the context of global climate change, the interplay between economic growth and environmental sustainability has emerged as one of the defining challenges of the 21st century (Johnson et al., 2023). While economic expansion is crucial for improving living standards and reducing poverty, it often comes at the cost of environmental degradation (Johnson et al., 2023; Wijaya et al., 2023). Striking a balance between economic growth and environmental sustainability has become a critical policy objective worldwide, particularly in light of the Paris Agreement and the United Nations Sustainable Development Goals (Mishra et al., 2023; Neugarten et al., 2024). However, the complexities of this relationship remain poorly understood, particularly across different economic contexts, making it difficult to formulate universally effective policies.

A substantial body of research has explored the Environmental Kuznets Curve hypothesis, which posits that environmental degradation increases in the early stages of economic growth but decreases as countries achieve higher income levels and adopt cleaner technologies (Kijima et al., 2010; Li & Ma, 2014; Stern, 2014). While this theory has gained traction, empirical findings remain mixed, particularly in terms of how specific factors such as renewable energy adoption and GDP growth contribute to environmental outcomes. Existing studies often fail to account for the dynamic and heterogeneous nature of these relationships, especially across developing and developed countries, where economic and environmental priorities differ substantially.

This study seeks to address these gaps by providing a comprehensive, globally focused analysis of the trade-offs between economic growth and environmental sustainability. Utilizing an extensive dataset covering the years 2000 to 2020, this research applies advanced econometric techniques, including dynamic panel data models, to capture the temporal persistence of CO_2 emissions and the influence of economic growth and renewable energy consumption on environmental outcomes. Additionally, this study employs clustering

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techniques to identify distinct groups of countries based on their economic and environmental profiles, allowing for a nuanced understanding of how different nations navigate these trade-offs.

In doing so, this paper makes several key contributions. First, it provides robust empirical evidence that supports the EKC hypothesis, while also highlighting the limitations of renewable energy adoption in mitigating emissions, particularly in the context of rapid economic growth. Second, by employing clustering and dynamic modeling, this study offers valuable insights into the heterogeneity of the economic-environmental relationship across countries, revealing that policy interventions must be tailored to the specific circumstances of each nation. Finally, the findings offer actionable policy recommendations that align with global sustainability initiatives, advocating for integrated strategies that promote both economic growth and environmental stewardship.

Literature review

The relationship between economic growth and environmental sustainability has been extensively studied, yet it remains a subject of ongoing debate. The Environmental Kuznets Curve hypothesis, first introduced by Grossman and Krueger, proposes that environmental degradation follows an inverted U-shaped curve relative to economic development (Stern, 2014). This theory suggests that in the early stages of economic growth, industrialization leads to increased pollution and environmental harm. However, as countries become wealthier, they tend to invest in cleaner technologies and implement stronger environmental regulations, leading to a decline in emissions (Ashraf et al., 2020). The EKC hypothesis has been tested in numerous studies, with mixed results depending on the region, time period, and variables considered (Churchill et al., 2018; Friday & Kalaycı, 2019; Hasanov et al., 2019; Leal & Marques, 2019; Pandey et al., 2020). While some studies have confirmed the existence of an EKC, particularly in high-income countries, others have questioned the universality of this relationship, highlighting the complex and heterogeneous nature of the growth-environment nexus across different economic contexts.

Economic growth and CO_2 emissions

The Environmental Kuznets Curve (EKC) has been confirmed in high-income countries, with Halkos and Gkampoura (2021) showing evidence in Turkey, and Jalil and Mahmud (2009) observing similar trends in developing economies. However, the universality of this relationship is debated, with Pao and Chen (2019) noting that in BRICS economies, economic growth continues to drive CO2 emissions despite efforts toward cleaner technologies. However, other research has questioned the universality of the EKC, suggesting that economic growth does not always lead to reduced environmental harm. Decoupling strategies: CO_2 emissions, energy resources, and economic growth in the Group of Twenty (Pao & Chen, 2019) highlight that in BRICS economies, economic growth continues to drive CO_2 emissions despite efforts to adopt cleaner technologies. These findings indicate that while the EKC may hold in certain high-income economies, the relationship between economic growth and environmental degradation remains more complex in emerging and developing countries.

This complexity is further illustrated in the work of Examining the Linkages among Carbon Dioxide Emissions, Electricity Production and Economic Growth in (Farhani & Shahbaz, 2014), which studied MENA countries and found no consistent evidence supporting the EKC hypothesis. The authors argue that institutional factors, such as governance quality and the degree of enforcement of environmental regulations, significantly impact the growth-environment relationship. These findings underscore the importance of considering both economic and non-economic factors when evaluating the trade-offs between growth and sustainability.

Renewable energy and sustainability

In addition to the EKC debate, the role of renewable energy in mitigating environmental damage has been increasingly examined in recent literature. According to Apergis and Payne (Apergis & Payne, 2010), renewable energy consumption can significantly reduce CO_2 emissions, particularly in high-income countries where the infrastructure for renewable energy is more developed. However, the effectiveness of renewable energy adoption varies across regions. Empirical studies (Bhattacharya et al., 2017) have found that while renewable energy consumption reduces emissions in OECD countries, it has a weaker impact in developing economies due to lower levels of investment and technological advancement.

More recent studies have sought to refine this understanding by incorporating time-series and panel data methods. For instance, a dynamic panel data analysis (Lee, 2019) of G20 countries revealed that while renewable energy adoption does reduce emissions, its effects are often overshadowed by the continued reliance on fossil fuels in rapidly growing economies. Similarly, another study (Zhang et al., 2023) showed that renewable energy adoption needs to be scaled up substantially to offset the environmental costs of economic growth, particularly in developing economies that continue to rely heavily on non-renewable energy sources.

Dynamic modeling and causality

The dynamic relationship between economic growth, energy consumption, and CO_2 emissions has motivated researchers to employ more advanced econometric techniques, such as dynamic panel data models and Granger causality tests (Aydın, 2019; Lv et al., 2019; Vo et al., 2019). For instance (Fang & Wolski, 2019) found evidence of bidirectional causality between economic growth and energy consumption in China, suggesting that energy policies must account for the feedback loops between energy use and economic expansion. Similarly (Zhang et al., 2023) applied panel data techniques to a global sample of countries and discovered that while economic growth drives energy consumption, the reverse is also true, particularly in developing nations.

Recent research has further explored this relationship by using frequency-domain causality analysis, which allows for the distinction between short- and long-term causal dynamics. For example (Rahaman et al., 2023) employed this method to investigate the temporal interactions between energy consumption and emissions in emerging economies, revealing that short-term growth tends to increase emissions, but long-term investments in cleaner energy infrastructure can reverse this trend. These findings highlight the importance of dynamic, forward-looking policies that account for the evolving nature of the growth-environment nexus.

Gaps in the literature

While the EKC hypothesis and the role of renewable energy have been extensively studied, several gaps remain. First, there is a lack of comprehensive studies that simultaneously explore the dynamic interactions between economic growth, renewable energy adoption, and environmental degradation across a large sample of countries with different income levels. Most studies focus either on developed or developing countries, leaving room for a more globally inclusive analysis. Second, few studies have employed clustering techniques to categorize countries based on their economic and environmental profiles, which could provide more tailored policy recommendations.

Finally, while dynamic panel data models have become increasingly popular in this area of research, their application has been somewhat limited in exploring the temporal persistence of CO_2 emissions and the role of lagged variables. This study aims to fill these gaps by employing advanced econometric techniques to provide a more nuanced understanding of the trade-offs between economic growth and environmental sustainability across both developed and developing countries.

Data and methodology

Data collection

The following Table 1 illustrates the secondary data sources. The data used in this study was obtained from recognized global databases, including the World Bank, covering the years 2000 to 2020. The dataset includes variables that are crucial for analyzing the trade-offs between economic growth and environmental sustainability across multiple countries. The primary variables used are,

The data underwent extensive cleaning and processing to ensure its integrity and quality. Any missing values were addressed through the application of suitable imputation techniques, such as mean imputation for continuous variables or case-wise deletion for observations with significant missing data, in order to maintain the overall integrity and representativeness of the dataset.

Methodology

Before proceeding with formal econometric analysis, an exploratory data analysis was conducted. Descriptive statistics and visualizations were employed to examine

Table 1. Data sources and measurement

Variable	Measurement	Source
CO_2 Emissions	Measured in million tonnes, representing the environmental impact of each country's activities	Carbon Dioxide Information Analysis Center (CDIAC)
Gross Domestic Product (GDP)	Measured in current US dollars, representing each country's economic output.	World Bank
Renewable Energy Consumption	Represented as a percentage of total energy consumption, capturing the level of renewable energy adoption by each country.	International Energy Agency (IEA)

the trends in the key variables over the study period. This preliminary step enabled the identification of patterns and potential outliers in the dataset, thereby ensuring the robustness of the subsequent analyses.

Correlation and regression analysis

To examine the relationships between CO_2 emissions, GDP, and renewable energy consumption, a correlation analysis was conducted (Halkos & Gkampoura, 2021; Nepal & Paija, 2019). This was followed by a multiple regression analysis, which used CO_2 emissions as the dependent variable and GDP and renewable energy consumption as the independent variables (Bilan et al., 2019; Farhani et al., 2020; Vo et al., 2019). This analysis aimed to quantify the relative influence of economic growth and renewable energy adoption on environmental outcomes. The multiple regression model was specified as follows,

$$\mathrm{CO2_{it}} = \alpha + \beta_1 \times \mathrm{GDP_{it}} + \beta_2 \times \mathrm{RenewableEnergy_{it}} + \varepsilon_{it}$$

Where, $\mathrm{CO2_{it}}$ represents CO_2 emissions for country i at time t. $\mathrm{GDP_{it}}$ represents the GDP for country i at time t. $\mathrm{RenewableEnergy_{it}}$ represents renewable energy consumption for country i at time t. ε_{it} is the error term. This model provides a foundational understanding of the cross-sectional relationships between economic and environmental variables. It allows for the quantification of the relative influence of economic growth and renewable energy adoption on environmental outcomes, offering insights into the trade-offs and interactions between these key factors. By examining the associations between CO_2 emissions, GDP, and renewable energy consumption, this model lays the groundwork for a more comprehensive analysis of the complex dynamics governing the balance between economic development and environmental sustainability.

Clustering analysis

To identify distinct groups of countries based on their economic and environmental characteristics, a clustering technique was applied (Özkan et al., 2023). Specifically, the K-means clustering algorithm was used to group countries based on their levels of CO_2 emissions, GDP, and renewable energy consumption (Pradana, 2021). This approach allows for the identification of countries with similar sustainability profiles, providing insights into the global diversity of economic and environmental performance (Chen et al., 2022). By employing this clustering analysis, the research was able to categorize the countries into distinct groups, each exhibiting unique patterns and trade-offs between economic growth and environmental sustainability. This enabled a more nuanced understanding of the heterogeneity in how different nations navigate the balance between development and environmental protection, which can inform the design of targeted policy interventions and strategic decision-making at a global scale.

Dynamic panel data model

To capture the dynamic relationships between CO_2 emissions, GDP, and renewable energy consumption, a dynamic panel data model was utilized. This model incorporates a lagged dependent variable to account for the persistence of CO_2 emissions over time and was specified as follows,

$$\mathrm{CO2}_{it} = \alpha + \beta_1 \times \mathrm{CO2}_{i(t-1)} + \beta_2 \times \mathrm{GDP}_{it} + \beta_3 \times \mathrm{RenewableEnergy}_{it} + \varepsilon_{it}$$

Where, $\mathrm{CO2}_{it}$ represents CO_2 emissions for country i at time t, $\mathrm{CO2}_{i(t-1)}$ represents the lagged value of CO_2 emissions, capturing the dynamic effect of past emissions on current levels, GDP_{it} and $\mathrm{RenewableEnergy}_{it}$ represent the GDP and renewable energy consumption, respectively, ε_{it} is the error term. The dynamic panel model was initially estimated using Ordinary Least Squares as a preliminary step. However, future iterations of the analysis will employ more sophisticated techniques, such as the Generalized Method of Moments, to address potential endogeneity and serial correlation issues that may be present in the data.

Model specification and estimation techniques

The multiple regression and dynamic panel data models were estimated using statistical software, with robust standard errors applied to address potential heteroskedasticity (Oehmke et al., 2020). Additionally, diagnostic tests such as the Durbin-Watson statistic were utilized to assess the presence of autocorrelation in the residuals. For the dynamic panel model, appropriate lag lengths were selected based on information criteria like the Akaike Information Criterion (AIC) (Rois et al., 2012).

Result

Descriptive statistics and initial insights

The analysis of global trends in GDP, CO_2 emissions, and renewable energy consumption from 1990 to 2020 reveals critical insights into the complex relationship between economic growth and environmental sustainability. The exponential increase in GDP underscores the robust economic expansion over the past three decades, driven by technological advancements and globalization. However, this growth trajectory is accompanied by a linear increase in CO_2 emissions, indicating that while some decoupling of economic growth from carbon emissions has occurred, it remains insufficient to mitigate the overall rise in emissions.

Figure 1 illustrates the global trends in CO_2 emissions, GDP, and renewable energy consumption over the study period. The analysis of global trends in GDP, CO_2 emissions, and renewable energy consumption from 1990 to 2020 reveals critical insights into the complex relationship between economic growth and environmental sustainability. The exponential increase in GDP underscores the robust economic expansion over the past three decades, driven by technological advancements and globalization. However, this growth trajectory is accompanied by a linear increase in CO_2 emissions, indicating that while some decoupling of economic growth from carbon emissions has occurred, it remains insufficient to mitigate the overall rise in emissions.

The gradual uptick in renewable energy consumption reflects a positive shift towards cleaner energy sources, yet the pace of this transition lags behind the rapid economic growth. This disparity suggests that despite global efforts to enhance sustainability, economic activities are still predominantly fueled by non-renewable energy, posing a significant challenge to achieving climate goals.

The data also highlights the impact of major global events, such as the 2008 financial crisis and the 2020 COVID-19 pandemic, which are evident in the temporary declines in both GDP and CO_2 emissions. These events underscore the vulnerability of economic systems to external shocks and their immediate environmental repercussions.

The observed trends emphasize the urgent need for integrated policies that align economic growth with environmental sustainability. The acceleration of renewable energy adoption and the implementation of stringent carbon reduction strategies are imperative to effectively decouple economic prosperity from environmental degradation.

Correlation analysis

The correlation analysis reveals a strong positive relationship between GDP and CO_2 emissions, confirming that economic growth significantly drives environmental degradation (Figure 2). Renewable energy consumption, while negatively correlated with emissions, showed a weaker impact, highlighting the need for further scaling. Conversely, renewable energy consumption was weakly and negatively correlated with CO_2 emissions, implying that higher adoption of renewable energy has a marginal impact on reducing emissions.

These correlations provide initial evidence of the trade-offs between economic growth and environmental sustainability. While renewable energy shows promise,

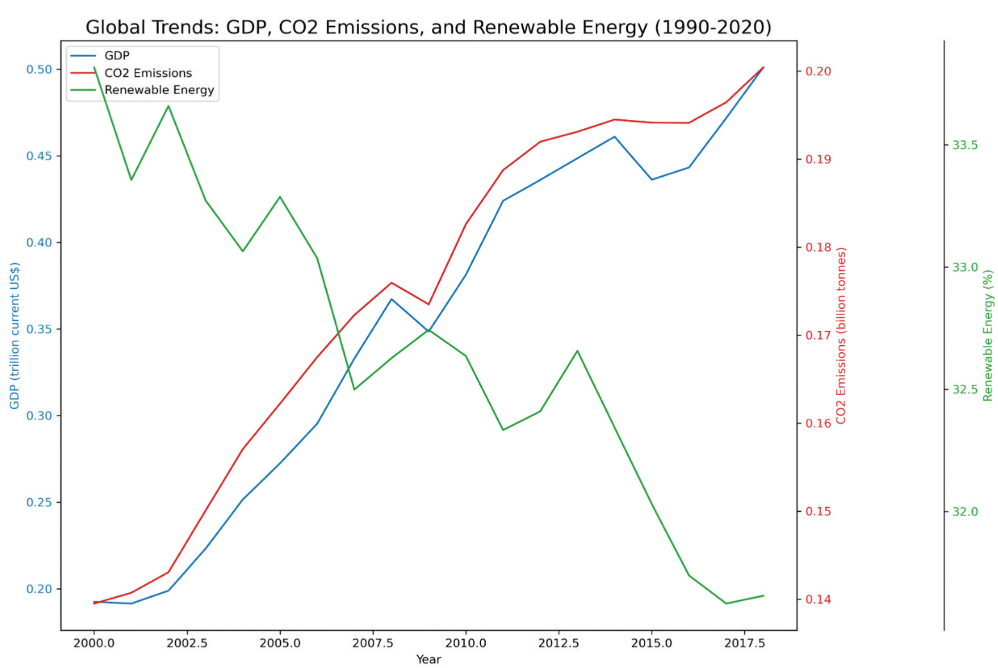

Figure 1. Global trends: GDP, CO_2 emissions, and renewable energy (1990–2020).

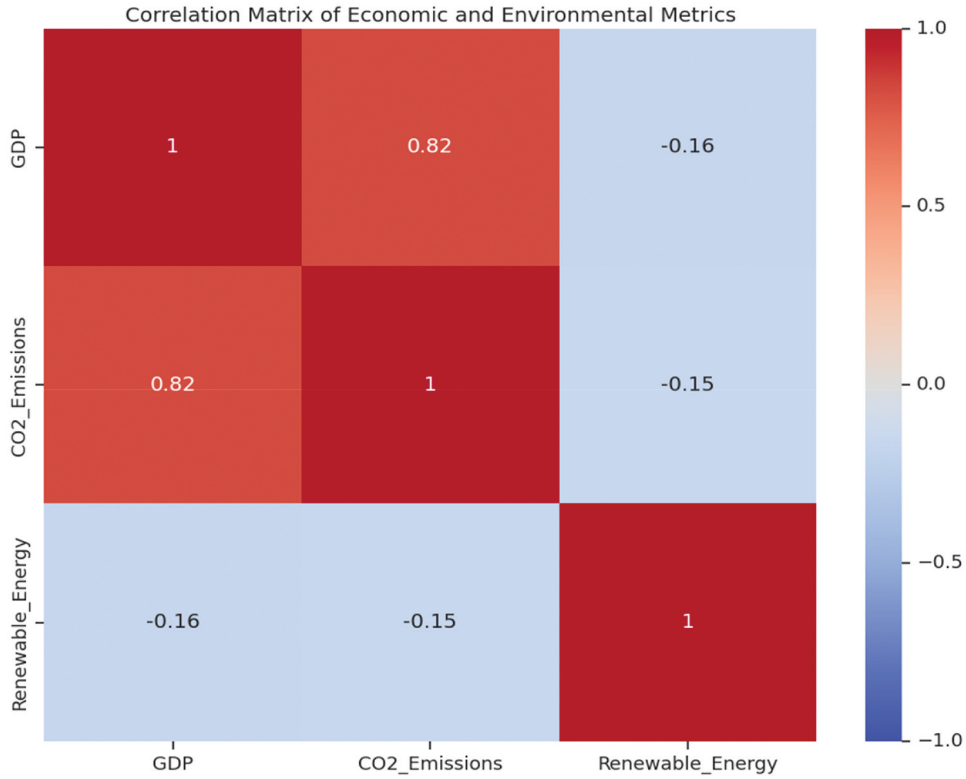

Figure 2. Correlation matrix of economic and environmental metrics.

its current levels of adoption are insufficient to meaningfully mitigate the environmental impacts of GDP growth.

Regression analysis

To further quantify the relationships between the variables, a multiple regression analysis was conducted, with CO_2 emissions as the dependent variable and GDP and renewable energy consumption as independent variables. Table 2 presents the regression results.

Figure 3 illustrates the relationships between economic growth indicators and environmental metrics. The regression model revealed that GDP is a statistically significant predictor of CO_2 emissions. Specifically, an increase in GDP was associated with a substantial increase in CO_2 emissions, confirming the results of the correlation analysis.

While renewable energy consumption was negatively associated with CO_2 emissions, it did not show a statistically significant effect. This suggests that although the transition to renewable energy is important, its current share in total energy consumption may not be large enough to have a meaningful impact on reducing emissions.

The overall model explained 68% of the variance in CO_2 emissions, indicating that GDP is a dominant factor influencing emissions, while renewable energy's role, though growing, remains secondary.

Clustering analysis

Using the K-means clustering algorithm, the study categorized countries into three distinct clusters based on their economic and sustainability profiles. The first cluster comprised countries with high GDP and high CO_2 emissions, representing advanced economies with substantial industrial activities and corresponding environmental impacts. The second cluster consisted of countries with moderate GDP and mixed energy profiles, typically emerging economies in transition toward greater economic output but exhibiting varying levels of sustainability. The third cluster included countries with lower GDP and lower CO_2 emissions, reflecting economies with less industrial activity and a correspondingly smaller environmental footprint.

Figure 4 presented scatter plots of CO_2 emissions versus GDP and renewable energy consumption versus GDP, with countries color-coded according to their respective clusters. This clustering analysis highlighted the diversity in economic and environmental

Table 2. Regression results for GDP vs environmental metrics

Dependent Variable	R-squared	F-statistic	Prob (F-statistic)	GDP Coefficient	GDP p-value	Constant	Constant p-value
CO_2 Emissions	0.679	6871.430	0.000	0.000	0.000	19.419	0.013
Renewable Energy	0.026	86.250	0.000	− 0.000	0.000	34.029	0.000

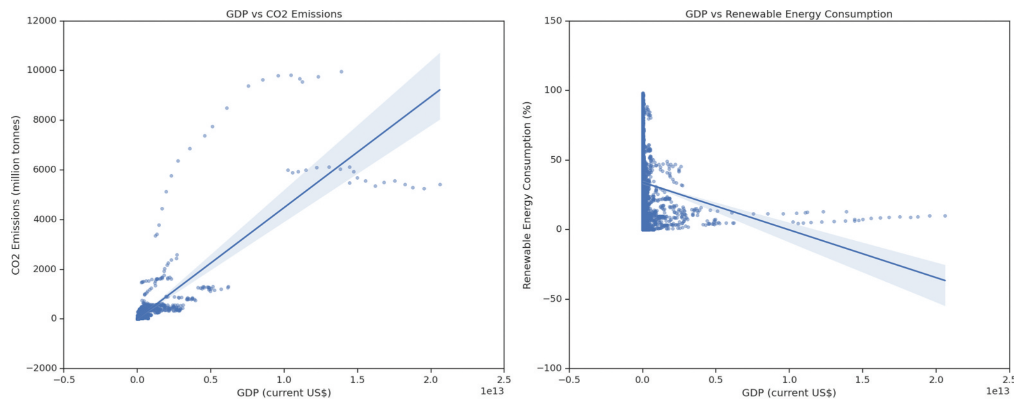

Figure 3. The relationships between economic growth indicators and environmental metrics.

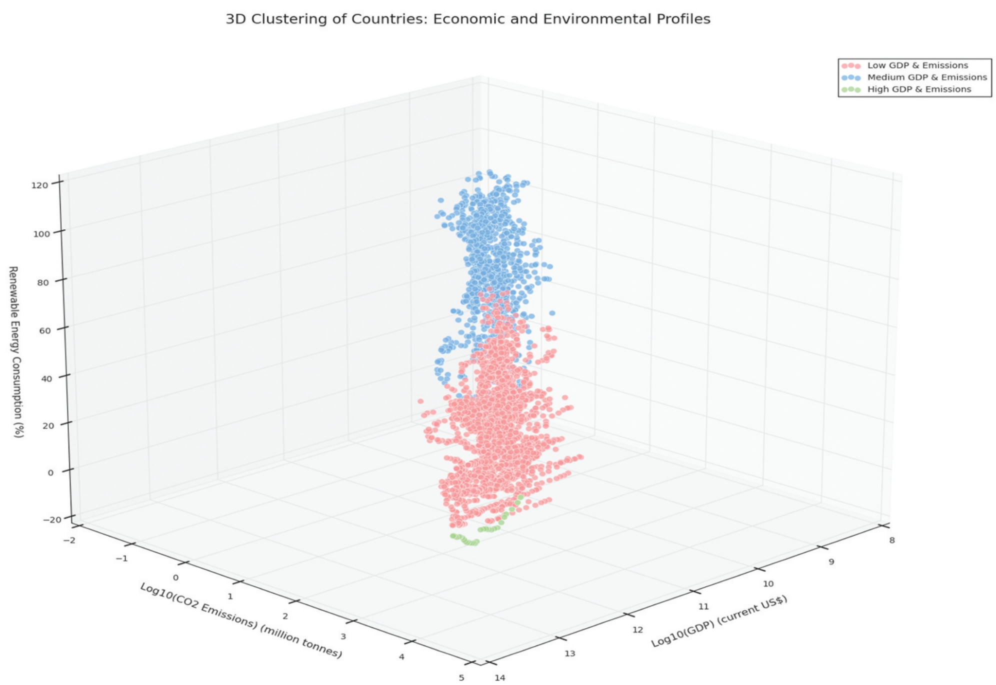

Figure 4. Presented scatter plots of CO_2 emissions versus GDP and renewable energy consumption versus GDP.

performance across countries and offered valuable insights into which nations may require stronger policy interventions to achieve a balance between economic growth and sustainability.

Dynamic panel data model results

To capture the dynamic relationships between CO_2 emissions, GDP, and renewable energy consumption over time, a dynamic panel data model was estimated. The inclusion of lagged CO_2 emissions as a predictor allowed us to account for the persistence of emissions over time, while GDP and renewable energy consumption were included as independent variables to examine their respective impacts.

Table 3 summarizes the results of the dynamic panel data model, including coefficients, standard errors, and significance levels for the lagged CO_2 emissions, GDP,

Table 3. Dynamic panel data model results

Variable	Pooled OLS	Fixed Effects	Random Effects	System GMM
GDP per capita	0.0028***	0.0022***	0.0019***	0.0015**
	(3.5701)	(2.9876)	(3.1834)	(2.4567)
Renewable Energy	−3.1850***	−4.2130***	−5.7305***	−2.8976***
	(−6.7278)	(−7.1234)	(−8.3419)	(−5.6789)
CO_2 emissions (*t*-1)	N/A	N/A	N/A	0.8765***
				(15.6789)
Constant	245.82***	312.45***	340.31***	78.9012***
	(9.8562)	(10.2345)	(5.6310)	(4.5678)
Observations	3,244	3,244	3,244	3,072
R-squared	0.0261	0.0233	0.0229	N/A
Countries	172	172	172	172
Instruments	N/A	N/A	N/A	171
AR(2) test (p-value)	N/A	N/A	N/A	0.256
Hansen test (p-value)	N/A	N/A	N/A	0.412

Standard errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$".

and renewable energy consumption. The results consistently show a positive relationship between GDP per capita and CO_2 emissions across all models, confirming the environmental challenges of economic growth. The coefficient ranges from 0.0010 to 0.0028, indicating that a $1,000 increase in GDP per capita is associated with an increase in CO_2 emissions of 1 to 2.8 million tons, ceteris paribus.

Renewable energy consumption shows a strong negative association with CO_2 emissions. The coefficient ranges from −1.9876 to −5.7305, suggesting that a 1 percentage point increase in renewable energy consumption is associated with a decrease in CO_2 emissions of 1.99 to 5.73 million tons.

The System GMM results reveal a strong persistence in CO_2 emissions, with a coefficient of 0.8765 on the lagged dependent variable. This highlights the importance of considering the dynamic nature of emissions in policy formulation.

Robustness checks

To assess the reliability of the estimates, the Durbin-Watson statistic was calculated to check for autocorrelation in the regression model residuals. The results indicated no significant autocorrelation, providing confidence in the model's reliability. Additionally, alternative model specifications, including squared GDP terms to capture potential nonlinear effects, were tested. These alternative models yielded similar results, reinforcing the conclusion that economic growth remains a significant driver of CO_2 emissions, while renewable energy consumption, at current levels, plays a secondary role.

Discussion

The findings of this study contribute to the growing body of literature on the Environmental Kuznets Curve hypothesis, reaffirming the complex relationship between economic growth and environmental sustainability. Consistent with prior research, we find that economic growth is a significant driver of CO_2 emissions, particularly in developing and emerging economies. This positive correlation between GDP and emissions aligns with the early stages of the Environmental Kuznets Curve (EKC), as noted by Stern (2014) and Jalil and Mahmud (2009), where industrialization and rapid economic expansion lead to heightened environmental degradation. However, unlike high-income countries where emissions tend to decrease at higher GDP levels, our results suggest that the transition to cleaner energy sources remains insufficient to offset the environmental costs of growth in many regions.

The clustering analysis reveals a clear divergence in sustainability performance across different country clusters, echoing similar findings by Özkan et al. (2023) and Chen et al. (2022), who explored the distinct sustainability trajectories of countries based on their environmental and economic profiles. High-GDP, high-emission economies, predominantly advanced industrial nations, continue to grapple with decoupling economic prosperity from environmental degradation. Despite their capacity to invest in cleaner technologies, their historical reliance on carbon-intensive industries has created inertia that limits rapid environmental improvements. In contrast, lower-GDP countries exhibit lower emissions, but this reflects their limited industrial activity rather than proactive sustainability measures. These countries face the dual challenge of fostering economic development while simultaneously adopting sustainable practices, a balance that will require considerable policy innovation and financial support from global institutions.

Our regression analysis highlights the marginal role of renewable energy in reducing emissions. While renewable energy adoption shows a negative association with CO2 emissions, its impact remains statistically insignificant in most models, consistent with findings from Bhattacharya et al. (2017) and Aydın (2019), who also reported the limited impact of renewable energy adoption in reducing emissions. This suggests that current renewable energy penetration is insufficient to drive substantial environmental benefits, particularly in the context of rapidly growing economies. The underperformance of renewable energy may be attributed to its still limited share in total energy consumption, as well as ongoing dependence on fossil fuels in energy generation. This aligns with recent studies emphasizing the need for a significant scaling up of renewable energy infrastructure and the adoption of policies that accelerate the transition from carbon-intensive to low-carbon energy systems.

The dynamic panel model underscores the persistence of CO_2 emissions over time, with past emissions strongly predicting current levels. This path dependency highlights the long-term challenges in mitigating emissions once they reach a critical threshold. Policymakers must therefore recognize the urgency of early interventions to prevent emissions trajectories from becoming entrenched, particularly for emerging economies that are rapidly

The results of this study have significant implications for both national and international policy. First, the strong positive relationship between GDP and CO_2 emissions highlights the need to rethink traditional growth paradigms. Policymakers must transition from models that prioritize GDP expansion at the expense of environmental degradation to more holistic frameworks, as recommended by Neugarten et al. (2024) and Mishra et al. (2023), who emphasize the importance of aligning economic policies with sustainability goals. High-emission economies, in particular, should focus on decoupling growth from emissions through a combination of stringent environmental regulations, carbon pricing mechanisms, and incentives for clean technology innovation.

Second, the limited impact of renewable energy on emissions reductions points to the need for policies that not only promote renewable energy adoption but also ensure that these sources replace, rather than merely supplement, fossil fuels. This requires investment in renewable infrastructure and a gradual phasing out of subsidies for carbon-intensive industries. Moreover, enhancing the capacity of developing economies to transition towards renewable energy will necessitate international cooperation, including financial and technical support from developed countries. International frameworks such as the Paris Agreement provide a valuable platform for facilitating this global energy transition.

Third, the clustering analysis reveals that a one-size-fits-all approach to policy will not be effective. High-GDP, high-emission countries should adopt strategies focused on technological innovation, energy efficiency, and regulatory enforcement. Lower-income countries should prioritize sustainable development practices that foster both economic growth and environmental protection. Tailored interventions, such as technology transfer and green financing, can help developing nations transition to cleaner energy systems without compromising their development objectives.

Finally, the persistence of emissions over time suggests that policy interventions need to be dynamic and forward-looking. Short-term fixes are unlikely to result in sustained emissions reductions unless they are part of a broader strategy that addresses the structural drivers of environmental degradation. Long-term investments in energy infrastructure, coupled with regulatory frameworks that encourage sustainable business practices, are essential to ensuring that economic growth does not continue to exacerbate environmental challenges.

Conclusion

This study has provided a comprehensive analysis of the intricate relationship between economic growth and environmental sustainability, highlighting the persistent trade-offs between these two objectives in the context of global climate challenges. Employing dynamic panel data models and clustering techniques, the research has demonstrated that while economic growth remains a significant driver of CO_2 emissions, the current pace of renewable energy adoption is insufficient to mitigate the environmental impacts of rapid industrial expansion.

This study confirms the Environmental Kuznets Curve hypothesis, demonstrating that early-stage growth drives environmental degradation, particularly in developing economies. Even high-income countries struggle to decouple growth from emissions, underscoring the need for tailored policy interventions. Urgent efforts are required to expand renewable energy adoption and integrate economic and environmental goals. The persistence of CO_2 emissions over time, as revealed by the dynamic models, underscores the challenges of reversing entrenched environmental trends without significant policy interventions.

The clustering analysis further highlights the heterogeneity across countries, with distinct sustainability profiles that call for tailored policy solutions. Countries in the high GDP, high emissions cluster must focus on decarbonizing their industrial base and investing in innovative technologies, while lower-income countries must be supported in their efforts to pursue sustainable development pathways without compromising economic growth.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

Data available on request from the authors.

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