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Renewable Energy Transition and Carbon Emissions Mitigation: A Panel Analysis of Middle- and High-Income Countries Beyond the EKC Framework

Transformacja w kierunku energii odnawialnej i ograniczanie emisji dwutlenku węgla. Analiza danych panelowych krajów o średnich i wysokich dochodach w ujęciu wykraczającym poza koncepcję środowiskowej krzywej Kuznetsa (EKC)

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Abstract: This study examines whether the Environmental Kuznets Curve (EKC) hypothesis adequately explains the relationship between economic growth and environmental degradation when key structural factors are taken into account. Using panel data for 15 middle-income and 15 high-income countries over the period 1990-2023, the analysis incorporates primary energy consumption, renewable energy use, and population growth into the traditional EKC framework to better capture the drivers of CO_2 emissions. Methodologically, the study employs panel econometric techniques that address cross-sectional dependence and heterogeneity, including appropriate unit root and cointegration tests, followed by long-run estimation and causality analysis. The findings indicate that in middle-income countries, CO_2 emissions are primarily driven by rising energy consumption and population growth, while renewable energy plays a mitigating role; income does not exhibit a significant long-run impact. In high-income countries, primary energy use increases emissions whereas renewable energy reduces them, while GDP and population growth remain insignificant. Causality analysis reveals strong bidirectional relationships between emissions and energy-related variables in both income groups. Overall, the study concludes that energy composition is more influential than income in determining environmental outcomes. These results highlight the importance of accelerating the transition to renewable energy as a central policy priority for reducing emissions across different stages of economic development.

Keywords: CO_2 emissions, renewable energy transition, economic growth, Environmental Kuznets Curve, panel data, middle-income countries, high-income countries, environmental pollution, SDG 7 – Affordable and Clean Energy, SDG 13 – Climate Action

Streszczenie: W niniejszym badaniu podjęto próbę weryfikacji, czy hipoteza środowiskowej krzywej Kuznetsa (EKC) adekwatnie wyjaśnia zależność między wzrostem gospodarczym a degradacją środowiska, z uwzględnieniem kluczowych czynników strukturalnych. Wykorzystując dane panelowe dla 15 krajów o średnich dochodach oraz 15 krajów o wysokich dochodach w okresie 1990–2023, analiza uwzględnia zużycie energii pierwotnej, wykorzystanie energii odnawialnej oraz wzrost liczby ludności w ramach tradycyjnego modelu EKC, co pozwala lepiej uchwycić determinanty emisji CO_2. Pod względem metodologicznym zastosowano panelowe techniki ekonometryczne uwzględniające zależności przekrojowe oraz heterogeniczność badanych jednostek, w tym odpowiednie testy pierwiastka jednostkowego i kointegracji, a następnie estymację zależności długookresowych oraz analizę przyczynowości. Wyniki wskazują, że w krajach o średnich dochodach emisja CO_2 jest determinowana przede wszystkim przez rosnące zużycie energii oraz wzrost liczby ludności, podczas gdy energia odnawialna przyczynia się do ich ograniczenia; dochód nie wykazuje istotnego wpływu w długim okresie. W krajach o wysokich dochodach zużycie energii pierwotnej zwiększa emisję, natomiast energia odnawialna ją ogranicza, podczas gdy PKB oraz wzrost liczby ludności pozostają statystycznie nieistotne. Analiza przyczynowości wskazuje na silne dwukierunkowe zależności między emisją a zmiennymi energetycznymi w obu grupach krajów. Ogólnie rzecz biorąc, badanie prowadzi do wniosku, że struktura zużycia energii wywiera większy wpływ na kształtowanie wyników środowiskowych niż poziom dochodu. Uzyskane rezultaty podkreślają znaczenie przyspieszenia transformacji w kierunku energii odnawialnej jako kluczowego priorytetu polityki redukcji emisji CO_2 na różnych etapach rozwoju gospodarczego.

Słowa kluczowe: Emisja CO_2, transformacja w kierunku energii odnawialnej, wzrost gospodarczy, środowiskowa krzywa Kuznetsa, dane panelowe, kraje o średnim dochodzie, kraje o wysokim dochodzie, zanieczyszczenie środowiska, SDG 7 – Czysta i dostępna energia, SDG 13 – Działania w dziedzinie klimatu

Introduction

Since the Industrial Revolution, rapid economic growth and rising energy demand have played a key role in speeding up environmental degradation. One of the most important results of this has been a substantial increase in carbon dioxide (CO_2) emissions, mainly caused by fossil fuel–based energy generation and widely seen as a leading cause of global climate change. As environmental concerns grow, countries worldwide are increasingly looking for ways to balance economic progress with environmental sustainability and climate goals.

The environmental impacts of macroeconomic and demographic factors, such as gross domestic product (GDP), primary energy consumption, renewable energy adoption, and population growth, differ considerably across countries, especially when income levels are taken into account. Countries at various stages of economic development tend to have different technological capabilities, energy efficiency practices, and levels of renewable energy use, which all influence their environmental performance (Halkos & Gkampoura 2021). As a result, the relationship between economic growth and environmental degradation is often analysed through the framework of the Environmental Kuznets Curve (EKC) hypothesis.

The EKC hypothesis proposes an inverted U-shaped relationship between economic growth and environmental degradation. During the initial phases of economic development, industrialization and higher energy use tend to worsen environmental damage. However, after reaching a certain income level, environmental quality may start to improve due to advancements in technology, changes in the economic structure, and stricter environmental regulations. Still, recent studies argue that income alone might not fully explain environmental outcomes when structural factors, such as the composition of energy consumption, are considered.

At the same time, demographic dynamics also play a crucial role in shaping environmental pressures. Population growth tends to boost energy demand and resource use, which in turn raises emission levels. However, the environmental impact of increasing populations can be mitigated by expanding renewable energy within the overall energy mix. A higher share of renewable energy has the potential to disconnect economic growth from carbon emissions and promote long-term environmental sustainability (Satici & Cakir 2021).

This study empirically analyses the factors influencing CO_2 emissions in middle-income and high-income countries by expanding the traditional EKC framework to incorporate energy structure and demographic variables. Specifically, the research examines how primary energy consumption, renewable energy use, economic growth, and population increase impact environmental outcomes across different income levels.

To provide a clearer analytical framework, the study is guided by the following research questions:

- Q1: Does the Environmental Kuznets Curve (EKC) hypothesis adequately explain the relationship between economic growth and CO_2 emissions when energy structure variables are included in the analysis?
- Q2: How do primary energy consumption, renewable energy consumption, and population growth influence CO_2 emissions in middle-income and high-income countries?
- Q3: Does renewable energy consumption play a significant role in mitigating carbon emissions across different income groups?

Based on the theoretical and empirical literature, the study tests the following hypotheses:

- H1: Primary energy use raises CO_2 emissions in both middle-income and high-income countries.
- H2: Renewable energy consumption reduces CO_2 emissions.
- H3: Population growth contributes positively to CO_2 emissions, particularly in middle-income countries.
- H4: Once energy structure variables are included, the explanatory power of the traditional EKC hypothesis weakens.

By addressing these questions and hypotheses, the study aims to provide evidence on how energy composition influences environmental outcomes and to offer policy-relevant insights for speeding up the shift to renewable energy in countries at various stages of economic development.

1. Literature Review

Understanding the drivers of carbon dioxide (CO_2) emissions has become a central issue in environmental economics as countries attempt to balance economic growth with climate change mitigation goals. A large body of research shows that environmental degradation is shaped by a complex interaction of economic development, energy consumption patterns, technological progress, globalization, and institutional factors. These determinants influence environmental outcomes differently across countries depending on their level of economic development and their energy structures.

A substantial portion of the literature examines the relationship between economic growth and environmental degradation through the Environmental Kuznets Curve (EKC) hypothesis. The EKC suggests an inverted U-shaped relationship between income and environmental degradation, implying that pollution increases during the early stages of economic development but begins to decline after a certain income threshold is reached. This improvement is generally attributed to technological progress, structural economic transformation, and the implementation of stricter environmental regulations. Several empirical studies support this hypothesis. For example, Alam et al. (2016) find evidence of an EKC relationship between economic growth and carbon emissions in major emerging economies, while Satici and Cakir (2021) highlight the role of international environmental policies and technological progress in improving environmental quality in higher-income economies.

Another important stream of research focuses on the role of energy consumption in shaping environmental outcomes. Energy use, particularly from fossil fuel sources, remains one of the primary contributors to greenhouse gas emissions. Empirical studies consistently demonstrate that increases in energy intensity and dependence on fossil fuels significantly contribute to rising CO_2 emissions. For instance, Akgerman and Topçu (2011) emphasize the importance of reducing emissions in the transportation sector by limiting fossil fuel consumption.

Similarly, Özçağ et al. (2017) show that energy intensity and fossil fuel dependency are key drivers of greenhouse gas emissions, while Karaağaç and Ceylan (2018) provide evidence that long-term increases in energy consumption are strongly associated with higher carbon emissions.

In recent years, increasing attention has been given to the role of renewable energy in mitigating environmental degradation. Renewable energy sources such as solar, wind, and hydroelectric power are widely recognized as essential components of sustainable energy systems that can reduce carbon emissions while supporting economic growth. Empirical evidence suggests that increasing the share of renewable energy in the energy mix contributes significantly to improvements in environmental quality. For example, Rahman (2024) finds that renewable energy consumption significantly reduces CO_2 emissions in major fossil-fuel-consuming countries, highlighting the importance of expanding clean energy infrastructure. Similarly, Kafeel et al. (2024) demonstrate that renewable energy policies and green innovation play a crucial role in enhancing environmental quality by supporting the transition toward low-carbon energy systems.

Beyond energy consumption, several studies also emphasize the role of structural and institutional factors in shaping environmental outcomes. Globalization, trade openness, and institutional quality can influence environmental performance by altering production structures, facilitating technological diffusion, and affecting environmental regulation. For instance, Oluç and Güzel (2021) examine the relationship between globalization and energy consumption and show that economic integration can influence environmental outcomes through increased energy demand. In addition, Kirikkaleli et al. (2023) highlight the role of environmental innovation in reducing consumption-based carbon emissions. Similarly, technological innovation and research and development (R&D) activities are widely recognized as key drivers of environmental improvement by promoting cleaner production processes and improving energy efficiency (Xu & Khan 2023).

Another important factor influencing environmental degradation is demographic dynamics. Population growth tends to increase energy demand and natural resource consumption, which can lead to higher levels of carbon emissions. However, the magnitude of this effect varies depending on technological capacity, economic development, and the energy structure of countries. Dharmapriya et al. (2025) demonstrate that energy consumption remains the primary driver of emissions across income groups, while institutional capacity and access to clean technologies differ significantly between high-income and middle-income economies.

Recent studies in the field of energy economics further highlight the importance of renewable energy investments in reducing carbon emissions. Widianingsih (2024) analyzes the effects of different types of renewable energy, carbon taxes, and economic growth on carbon emissions using panel data for 47 countries between 2010 and 2020. The results show that wind and solar energy significantly reduce carbon emissions in terms of both electricity generation and installed capacity. Hydropower capacity also contributes to emission reductions, although electricity production from hydropower does not exhibit a statistically significant effect. In contrast, the presence of carbon taxes and GDP levels do not have a significant impact on carbon emission levels. These findings emphasize the importance of expanding renewable energy investments, particularly in wind and solar power, to achieve effective emission reductions.

Similarly, Huang (2024) investigates the multidimensional relationship between renewable energy deployment and CO_2 emissions in high-income countries. Using panel data for 33 high-income economies over the period 1996–2019, the study finds that the decarbonization effects of renewable energy vary across different components of emissions. Renewable energy development has increasingly reduced production-based emissions, particularly those associated with domestic supply chain activities. However, its influence on emissions embodied in exports and direct end-user emissions remains relatively limited. Moreover, the expansion of renewable energy does not appear to increase emissions embodied in imports, suggesting that renewable energy policies do not necessarily lead to carbon leakage. These findings indicate that climate policies in high-income countries should consider the structural composition of emissions to maximize the effectiveness of decarbonization strategies.

Despite the extensive literature on economic growth, energy consumption, and environmental degradation, several important research gaps remain. First, many empirical studies primarily focus on the EKC hypothesis and emphasize income effects while paying limited attention to the composition of energy consumption. Second, existing research often treats countries as homogeneous groups, overlooking structural differences between middle-income and high-income economies. Third, relatively few studies simultaneously examine primary energy consumption, renewable energy adoption, and demographic dynamics within a unified empirical framework.

This study aims to address these gaps by extending the traditional EKC framework and incorporating energy structure and population dynamics into the analysis. Using panel data for 15 middle-income and 15 high-income countries between 1990 and 2023, the study provides a comparative assessment of how primary energy consumption, renewable energy use, economic growth, and population growth influence CO_2 emissions across different income groups. By focusing on the role of energy composition, the research contributes to the growing literature that emphasizes the importance of the renewable energy transition as a key strategy for achieving environmental sustainability beyond income-based explanations.

2. Environmental and Economic Sustainability Across Income Groups

Sustainable development involves balancing economic growth and environmental protection without sacrificing the needs of future generations (Brundtland 1987). High- and middle-income countries vary significantly in their ability to achieve this balance, which directly influences their CO_2 emission trajectories.

High-income countries generally demonstrate stronger environmental sustainability efforts. They have greater financial resources, advanced technology, and institutional capacity to expand renewable energy, enhance energy efficiency, and enforce strict environmental regulations. Northern European countries and Germany's Energiewende policy are prominent examples of successful large-scale decarbonization initiatives (Buchan 2012; Höhne et al. 2020). However, these nations still bear the legacy of high cumulative historical emissions from early industrialization.

Middle-income countries, on the other hand, face a tougher trade-off between rapid economic growth and environmental protection. Growing energy demand is mostly met by fossil fuels, and environmental regulations are often weaker or not consistently enforced (Güney 2021). Although many countries, especially China, have significantly expanded renewable energy capacity in the last decade, coal and oil still make up the majority of the energy mix (Chen & Lees 2016).

From an economic sustainability perspective, high-income countries benefit from diversified economies, strong financial systems, and higher human capital, making them more resilient to external shocks (OECD 2019). Middle-income countries remain more vulnerable to commodity price fluctuations, external debt cycles, and balance-of-payments crises, while also struggling with higher income inequality (Yeldan 2006; Palma 2011).

These structural differences indicate that the factors influencing CO_2 emissions and the efficacy of policy instruments may vary systematically across income groups. High-income nations are better positioned to decouple economic growth from emissions through technological advancements and regulatory measures, whereas middle-income countries continue to face emissions pressures driven by energy-intensive development and population growth. Consequently, this research analyses the two groups independently to formulate policy recommendations tailored to each income category.

3. Econometric Analysis and Findings

3.1. Methodology

This study explores how factors such as energy consumption, economic growth, and population changes influence environmental pollution in middle- and high-income countries. Using panel data from 1990 to 2023, the analysis leverages annual data to identify trends over time. The data sources include the World Bank's World Development Indicators (WDI) and the BP Statistical Review of World Energy. To address issues related to scale differences and heteroscedasticity, all variables were converted to their natural logarithmic forms before analysis. This transformation improves the comparability of variables and enhances the reliability of the regression results. The empirical model used is outlined below, along with a detailed description of the country groups and variables included.

Model:

$$LCO_2 = \beta_0 + \beta_1 BET + \beta_2 KBGSYH + \\ + \beta_3 YET + \beta_3 NA + \sigma_{it}$$

In the equation, $\beta_0 \ldots \beta_4$ represent the coefficients, and represents the error term.

The table 1 includes the relevant country groups.

The analysis focuses on selected middle-income and high-income countries for which complete data sets were available. The table 2 details the variables employed, their abbreviations, and the data sources.

Among the variables used, population growth is expressed as a percentage, while all other variables are measured on a per capita basis. The analysis starts with the group of middle-income countries, and the initial findings will focus on this group.

3.2. Findings for the Middle-Income Country Group

Econometric analysis starts by assessing cross-sectional dependence among panel units using the Pesaran Cross-sectional Dependence (CD) test. The table 3 displays the test results, providing insights into whether the countries in the sample are interdependent.

The Pesaran CD test results shown in the table indicate that the p-values for the variables LCO_2, LPEC, LGDP, LREC, and LPG are all below the 0.05 significance level. Therefore, the null hypothesis of no cross-sectional dependence (H_0) is rejected, confirming the presence of cross-sectional dependence among the variables. Based on this finding, the analysis continues with a second-generation panel unit root test that considers this dependence, specifically the Cross-sectionally Augmented Im, Pesaran, and Shin (CIPS) test.

The CIPS unit root test results shown in the table indicate that, at the level, the absolute values of the t-bar statistics for all variables are below the critical value at the 5% significance level (Cv5). This suggests that none of the variables are stationary in their current form and therefore contain a unit root. To address this non-stationarity, the variables were first-differenced. After this transformation, the test results confirm that all variables reached stationarity, meeting the requirements for further analysis.

The fact that the variables only become stationary after first differencing suggests that cointegration analysis is appropriate for examining their long-term relationships.

Table 1. List of Selected Middle-Income and High-Income Countries
This table lists the countries included in the sample and groups them into middle-income and high-income categories. It clarifies which economies are compared in the empirical analysis.

Middle-Income Countries				
Argentina	Algeria	India	Morocco	Thailand
Bangladesh	Colombia	Malaysia	Egypt	Türkiye
Brazil	Indonesia	Mexico	South Africa	China
High-Income Countries				
Australia	Finland	Greece	Japan	Spain
Belgium	France	Hungary	New Zealand	USA
Canada	Germany	Ireland	Russia	Chile

Table 2. Variables, Abbreviations, and Data Sources
This table defines all variables used in the study, provides their abbreviations, and identifies the data sources. It helps the reader interpret the model notation and the data provenance.

Variable Name	Abbreviation	Database
Carbon Dioxide Emissions	CO2	WDI
Primary Energy Consumption	PEC	BP
Gross Domestic Product	GDP	WDI
Renewable Energy Consumption	REC	BP
Population Growth	PG	WDI

Table 3. Pesaran Cross-Sectional Dependence (CD) Test Results for Middle-Income Countries
This table reports the Pesaran CD test results for the middle-income panel variables. It indicates whether cross-sectional dependence is present and needs to be accounted for in estimation.

Variable Name	CD-Test	P-value
LCO2	40.96	0
LPEC	45.04	0
LGDP	55.06	0
LREC	27.58	0
LPG	34.18	0

Table 4. CIPS Panel Unit Root Test Results for Middle-Income Countries
This table reports the CIPS unit root test results for the middle-income panel, at levels and differences. It shows the stationarity properties of the variables used in subsequent long-run analysis.

LEVEL					
Variable Name	t-bar	Cv10	Cv5	Cv1	p-value
LCO2	-1.437	-2.14	-2.25	-2.44	0.915
LPEC	-1.824	-2.14	-2.25	-2.44	0.413
LGDP	-1.910	-2.14	-2.25	-2.44	0.283
LREC	-1.978	-2.14	-2.25	-2.44	0.196
LPG	-1.807	-2.14	-2.25	-2.44	0.181
1. VARIANCE					
ΔLCO_2	-3.409	-2.14	-2.25	-2.44	0
ΔLPEC	-3.786	-2.14	-2.25	-2.44	0
ΔLGDP	-3.094	-2.14	-2.25	-2.44	0
ΔLREC	-3.266	-2.14	-2.25	-2.44	0
ΔLPG	-4.305	-2.14	-2.25	-2.44	0

However, before conducting the cointegration tests, it is essential to check the data for cross-sectional dependence and slope homogeneity to ensure the results are valid and reliable. The results of the Breusch-Pagan LM test for cross-sectional dependence and the Swamy-S test for slope homogeneity are summarized in the table 5.

The Breusch-Pagan LM test results shown in the table indicate a p-value below 0.05, confirming the presence of cross-sectional dependence among the units. Regarding the Swamy-S test, the Prob > chi2 value is also less than 0.05, indicating that the model is not homogeneous.

Therefore, it is necessary to use cointegration tests that account for both cross-sectional dependence and heterogeneity characteristics typical of panel data. To this end, the Gengenbach, Urbain, and Westerlund panel cointegration test has been utilized in this analysis. The results of this cointegration test are shown in the table 6.

Hypotheses of the Gengenbach et al. Cointegration Test:

- H_0: There is no cointegrating relationship.
- H_1: There is a cointegrating relationship.

The results of the Gengenbach et al. cointegration test show that the p-value for the lagged dependent variable yt−1 is less than or equal to 0.01. This significant finding leads to rejecting the null hypothesis (Ho), confirming a cointegrating relationship between the dependent variable and the explanatory variables. Based on this, the analysis continues to examine the long-term dynamics among these variables using the DOLSMG estimator. The estimation results from the DOLSMG method are summarized in the table 7.

The coefficients reported in Table 7 represent the long-run elasticities of the explanatory variables with respect to CO_2 emissions. The results indicate that primary energy consumption, renewable energy consumption, and population growth have statistically significant effects on emissions, whereas GDP does not show a significant long-run relationship.

Specifically, a 1% increase in primary energy consumption is associated with a 0.21% increase in CO_2 emissions. In contrast, renewable energy consumption has a mitigating effect, as a 1% increase in renewable energy use leads to an estimated 0.55% reduction in emissions. Population growth also contributes positively to emissions, with a 1% increase corresponding to a 0.12% rise in CO_2 emissions. Overall, these findings highlight the critical role of energy structure in shaping environmental outcomes and underline the importance of expanding renewable energy to mitigate carbon emissions.

Country-level estimates, reported in Appendix 1 Table 8, reveal similar patterns. In many middle-income countries, higher primary energy consumption is associated with increased emissions, while greater renewable energy use contributes to emission reductions. For instance, renewable energy consumption significantly reduces emissions in countries such as Argentina, Bangladesh, Brazil, Colombia, and China, whereas primary energy consumption tends to increase emissions in countries including Brazil, Indonesia, Morocco, Malaysia, and Türkiye. Population growth also contributes to higher emissions in several cases.

Overall, the country-specific results confirm the aggregate findings, indicating that fossil-based energy consumption generally increases carbon emissions, while renewable energy plays a key role in mitigating environmental degradation. To further examine the dynamic relationships among the variables, the Dumitrescu-Hurlin panel causality test was conducted. The results of this analysis are presented in the table 9.

Hypotheses for the Dumitrescu-Hurlin Panel Causality Test:

- Ho: No causality exists between the variables across the panel.
- H1: At least one causal relationship exists among the variables in the panel.

Table 5. Breusch-Pagan LM Test for Cross-Sectional Dependence and Swamy-S Slope Homogeneity Test Results (Middle-Income Countries)

This table reports the Breusch–Pagan LM test and the Swamy-S slope homogeneity test for the middle-income group. It indicates whether the panel exhibits cross-sectional dependence and heterogeneous slopes.

Breusch-Pagan LM Test		
Test	Statistic	P-value
LM	1007	0
Homogeneity Test		
Test	Chi2(70)	Prob>Chi2
Swamy-S	277.13	0

Table 6. Gengenbach, Urbain, and Westerlund Panel Cointegration Test Results (Middle-Income Countries)

This table reports the panel cointegration test results for the middle-income group. It indicates whether a long-run relationship exists between CO_2 emissions and the explanatory variables.

Gengenbach, Urbain, and Westerlund Panel Cointegration Test			
d.y	coef	t-bar	P-val*
y(t-1)	-1.357	-4.983	<=0.01

Table 7. Dynamic Ordinary Least Squares Mean Group (DOLSMG) Long-Run Estimation Results (Middle-Income Countries)

This table reports the DOLSMG long-run coefficient estimates for the middle-income group. It shows how energy use, renewables, GDP, and population are associated with CO_2 emissions in the long run.

Variable	Beta	t-stat
ΔLPEC	0.2156	3.278
ΔLGDP	0.3088	1.88
ΔLREC	-0.5571	-9.99
ΔLPG	0.1254	2.272

Table 9. Dumitrescu-Hurlin Panel Causality Test Results (Middle-Income Countries)

This table reports the Dumitrescu-Hurlin panel causality test results for the middle-income group. It indicates the direction(s) of predictive relationships among CO_2 emissions and the explanatory variables.

Direction of Relationship	Z-bar	P-value
ΔLPEC à ΔLCO$_2$	2.3473	0.018
ΔLCO$_2$ à ΔLPEC	18.078	0
ΔLGDP à ΔLCO$_2$	0.0772	0.938
ΔLCO$_2$ à ΔLGDP	19.469	0
ΔLREC à ΔLCO$_2$	169.52	0
ΔLCO$_2$ à ΔLREC	4.7058	0
ΔLPG à ΔLCO$_2$	3.7197	0.002
ΔLCO$_2$ à ΔLPG	5.6727	0

The causality analysis results reveal a two-way causal relationship between primary energy consumption and carbon dioxide emissions, as well as between renewable energy consumption and carbon dioxide emissions. Additionally, the results show a one-way causal effect from carbon dioxide emissions to per capita GDP and from population growth to carbon dioxide emissions. Variables with bidirectional causality are understood as mutually influencing each other. The next section of the econometric analysis will focus on the findings related to the high-income country group.

3.3. Findings for the High-Income Country Group

The table 10 summarizes the results of the cross-sectional dependence test conducted on the variables.

As shown by the Pesaran CD test statistics in the table, all variables have p-values below the 0.05 significance level, indicating cross-sectional dependence among them. Therefore, the Cross-sectionally Augmented Im, Pesaran, and Shin (CIPS) test was used for unit root analysis.

The results of the CIPS unit root test show that, at their level values, the absolute t-bar statistics for the variables are lower than the critical value at the 5% significance level, indicating that the variables are non-stationary in levels and contain a unit root. Since the variables become stationary after first differencing, cointegration analysis was considered appropriate. The results of the Breusch-Pagan LM test for cross-sectional dependence and the Swamy-S test for slope homogeneity are summarized in the table 12.

The results of the Breusch-Pagan LM test indicate a p-value below 0.05, confirming the existence of cross-sectional dependence among the units. Similarly, the Swamy-S test produces a prob > chi2 value less than 0.05, which implies that the model demonstrates slope homogeneity. Considering these results, the study advanced by applying the Gengenbach, Urbain, and Westerlund panel cointegration test. The findings from this cointegration analysis are presented in the table 13.

According to the Gengenbach panel cointegration test results, the significance of the lagged dependent variable y(t-1)' was evaluated, and the p-value was found to be greater than or equal to 0.1. Therefore, the null hypothesis (Ho) is rejected, indicating the presence of a long-term cointegration relationship. To estimate the long-run parameters, the Dynamic Ordinary Least Squares Mean Group (DOLSMG) estimator was used. The results of this estimation are shown in table 14.

Table 14 presents the long-run estimation results obtained using the DOLSMG estimator for high-income countries. The findings indicate that primary energy consumption and renewable energy consumption have statistically significant effects on CO_2 emissions, whereas GDP and population growth do not show significant long-run relationships.

Specifically, a 1% increase in primary energy consumption is associated with a 0.66% rise in CO_2 emissions, highlighting the continuing environmental impact of fossil-based energy use even in advanced economies. In contrast, renewable energy consumption contributes to emission reductions, with a 1% increase in renewable energy use leading to an estimated 0.17% decrease in emissions.

Country-level results, presented in Appendix 1 table 15, reveal broadly similar patterns across the high-income sample. In many countries, higher primary energy consumption is associated with increased emissions, while renewable energy adoption tends to reduce emissions. For example, primary energy consumption significantly increases emissions in countries such as Chile, France, Greece, Spain, and the United States, whereas renewable energy consumption contributes to emission reductions in several economies, including Belgium, Hungary, Ireland, New Zealand, Russia, and the United States.

Table 10. Pesaran Cross-Sectional Dependence (CD) Test Results for High-Income Countries
This table reports the Pesaran CD test results for the high-income panel variables. It indicates whether cross-sectional dependence is present in the high-income group.

Variable Name	CD-Test	P-value
LCO2	24.19	0
LPEC	22.53	0
LGDP	52.75	0
LREC	24.44	0
LPG	4.36	0

Table 11. CIPS Panel Unit Root Test Results for High-Income Countries
This table reports the CIPS unit root test results for the high-income panel, at levels and differences. It shows whether variables are stationary and supports the choice of subsequent tests and estimators.

LEVEL					
Variable Name	t-bar	Cv10	Cv5	Cv1	p-value
LCO2	-1.93	-2.14	-2.25	-2.44	0.254
LPEC	-1.254	-2.14	-2.25	-2.44	0.983
LGDP	-1.87	-2.14	-2.25	-2.44	0.34
LREC	-1.755	-2.14	-2.25	-2.44	0.524
LPG	-1.934	-2.14	-2.25	-2.44	0.250
1. VARIANCE					
ΔLCO_2	-2.686	-2.14	-2.25	-2.44	0
ΔLPEC	-3.78	-2.14	-2.25	-2.44	0
ΔLGDP	-3.636	-2.14	-2.25	-2.44	0
ΔLREC	-3.42	-2.14	-2.25	-2.44	0
ΔLPG	-3.823	-2.14	-2.25	-2.44	0

Table 12. Breusch-Pagan LM Test for Cross-Sectional Dependence and Swamy-S Slope Homogeneity Test Results (High-Income Countries)
This table reports the Breusch-Pagan LM test and the Swamy-S slope homogeneity test for the high-income group. It indicates whether dependence and slope heterogeneity should be considered in the modelling strategy.

Breusch-Pagan LM Test		
Test	Statistic	P-value
LM	773.9	0
Homogeneity Test		
Test	Chi2(70)	Prob>Chi2
Swamy-S	323.05	0

Table 13. Gengenbach, Urbain, and Westerlund Panel Cointegration Test Results (High-Income Countries)
This table reports panel cointegration test results for the high-income group. It indicates whether CO_2 emissions and the explanatory variables share a long-run equilibrium relationship.

Gengenbach vs Test			
d.y	Coef	t-bar	P-val*
y(t-1)	-1.179	-4.366	<=0.01

Table 14. Dynamic Ordinary Least Squares Mean Group (DOLSMG) Long-Run Estimation Results (High-Income Countries)
This table reports the DOLSMG long-run coefficient estimates for the high-income group. It shows the long-run relationships between CO_2 emissions and energy, renewables, GDP, and population.

Variable	Beta	t-stat
ΔLPEC	0.6699	6.318
ΔLGDP	0.0466	.8301
ΔLREC	-0.1766	-8.116
ΔLPG	0.1038	.6119

Table 16. Dumitrescu-Hurlin Panel Causality Test Results (High-Income Countries)
This table reports the Dumitrescu-Hurlin panel causality test results for the high-income group. It indicates the direction(s) of predictive relationships between CO_2 emissions and the explanatory variables.

Direction of Relationship	Z-bar	P-value
ΔLPEC à ΔLCO_2	8.4771	0
ΔLCO_2 à ΔLPEC	5.4137	0
ΔLGDP à ΔLCO_2	0.0933	0.925
ΔLCO_2 à ΔLGDP	3.6723	0.002
ΔLREC à ΔLCO_2	125.88	0
ΔLCO_2 à ΔLREC	3.2055	0.001
ΔLPG à ΔLCO_2	14.041	0
ΔLCO_2 à ΔLPG	9.3110	0

Overall, these findings reinforce the central role of energy composition in shaping environmental outcomes in high-income countries. Despite technological progress and higher income levels, fossil-based energy consumption remains a major driver of emissions, while the expansion of renewable energy plays a key role in mitigating environmental degradation.

The causality analysis revealed a two-way causal relationship between primary energy consumption and carbon dioxide emissions, as well as between renewable energy consumption and emissions. Similarly, population growth and emissions also show mutual causality. In contrast, the results indicate a one-way causal effect from per capita GDP to emissions.

Conclusion

This study examines the factors driving CO_2 emissions in 15 middle-income and 15 high-income countries during 1990-2023, explicitly moving beyond the traditional Environmental Kuznets Curve framework by including primary energy consumption, renewable energy use, and population growth.

The long-term estimates show that income per capita does not have a statistically significant impact on CO_2 emissions in either income group. This result suggests that once structural energy variables are incorporated into the analysis, the explanatory power of income-centred approaches such as the traditional EKC framework becomes limited. In other words, economic growth alone does not appear to automatically lead to environmental improvements after a certain income level unless the structure of energy consumption also changes. This aligns with recent research indicating that structural factors, especially energy consumption patterns, are more influential in shaping environmental outcomes than income growth alone (Satici & Cakir 2021; Rahman 2024).

Instead, energy structure is the main factor: primary (mostly fossil-based) energy use significantly increases emissions in both middle-income (elasticity = 0.21) and high-income countries (elasticity = 0.66), while renewable energy use consistently reduces emissions (elasticity = −0.55 and −0.17, respectively). These findings broadly align with previous research that emphasizes the strong connection between fossil fuel use and carbon emissions, as well as the role of renewable energy in reducing them (Alam et al. 2016; Xu & Khan 2023). Population growth has a positive and significant impact only in middle-income countries, supporting the idea that demographic pressures continue to increase environmental challenges in fast-growing economies (Dharmapriya et al. 2025).

The causality analysis further uncovers strong two-way relationships between CO_2 emissions and both primary and renewable energy consumption in the two country groups. This shows that energy usage patterns and environmental outcomes influence each other mutually, emphasizing the key role of energy policy in fighting climate change.

The insignificant effect of GDP per capita in both country groups can be interpreted in several ways. First, the inclusion of energy consumption variables in the model may capture much of the environmental impact that is often indirectly attributed to economic growth. Second, economic growth does not necessarily translate into higher emissions uniformly across countries, particularly when technological capacity, environmental regulations, and energy efficiency differ significantly. In high-income countries, advanced technologies and stricter environmental policies may weaken the direct relationship between income growth and emissions. In middle-income countries, the environmental impact of growth may depend more heavily on whether expanding economic activity is supported by fossil-based or renewable energy systems.

From a policy perspective, the findings highlight key differences between middle-income and high-income countries. In middle-income nations, increasing energy demand driven by economic growth and population increases continues to put upward pressure on emissions. Therefore, policies in these countries should focus on accelerating the deployment of renewable energy infrastructure, enhancing energy efficiency, and reducing reliance on fossil fuels. Simultaneously, building institutional capacity and strengthening regulatory frameworks are crucial for supporting sustainable energy transitions.

In contrast, high-income countries generally have greater technological capabilities, financial resources, and institutional capacity to implement advanced decarbonization strategies. For these countries, policy priorities should include increasing investments in clean energy innovation, strengthening carbon pricing mechanisms, and encouraging technological breakthroughs in areas such as energy storage, smart grids, and green hydrogen. These measures can further reduce emissions even in economies where energy systems are already fairly efficient.

Furthermore, international cooperation and financial support systems are essential for advancing the global energy transition. Middle-income countries often face financial, technological, and institutional challenges that hinder their ability to quickly adopt renewable energy technologies. Greater access to climate finance, technology transfer programs, and multilateral collaboration efforts can help address these structural obstacles. Policies that promote research and development in green technologies, along with expanding renewable energy capacity, can significantly support long-term reductions in carbon emissions. These initiatives also align closely with global sustainability goals, especially the United Nations Sustainable Development Goal 7 (Affordable and Clean Energy) and the Sustainable Development Goal 13 (Climate Action).

In conclusion, achieving significant and lasting reductions in CO_2 emissions requires focusing on the shift to renewable energy in climate policy development. The results show that structural changes in energy systems, rather than income-driven technological progress alone, are key to improving environmental outcomes across countries at different stages of economic development.

Limitations and Future Research

Despite its contributions, this study has several limitations that should be acknowledged. First, the analysis focuses on a selected sample of middle-income and high-income countries, which may limit the relevance of the findings to other income groups or regions. Second, the study relies on aggregated macroeconomic indicators from international databases, which may not fully capture country-specific structural differences in energy systems and environmental policies. Third, although the panel econometric techniques used address cross-sectional dependence and heterogeneity, other factors such as technological innovation, institutional quality, or policy stringency were not explicitly included in the model. Future research could expand the analysis by incorporating variables related to technological development, environmental regulations, or financial development, as well as examining a broader range of countries or employing different econometric methods.

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Appendix 1

Table 8. Country-Specific DOLSMG Long-Run Estimation Results (Middle-Income Countries)
This table reports country-specific DOLSMG long-run estimates for the middle-income economies. It highlights cross-country variation in the long-run effects of energy use and renewables on CO_2 emissions.

Country	Variable	Beta	t-stat
Argentina	ΔLPEC	-0.1443	-0.1989
	ΔLGDP	-0.0196	-0.0548
	ΔLREC	-0.5132	-3.584
	ΔLPG	-0.1420	-1.737
Bangladesh	ΔLPEC	-0.7299	-0.1989
	ΔLGDP	-1.2990	-1.985
	ΔLREC	-1.2810	-4.404
	ΔLPG	0.0943	0.7071
Brazil	ΔLPEC	0.9963	3.019
	ΔLGDP	0.6088	1.780
	ΔLREC	-0.4804	-2.885
	ΔLPG	0.2076	0.7961
Algeria	ΔLPEC	0.3441	1.291
	ΔLGDP	-0.6139	-2.138
	ΔLREC	-0.0963	-1.798
	ΔLPG	-0.2742	-1.567
Colombia	ΔLPEC	-0.3309	-0.4636
	ΔLGDP	4.1670	2.706
	ΔLREC	-1.1180	-5.483
	ΔLPG	0.1655	1.732
Indonesia	ΔLPEC	0.5863	3.773
	ΔLGDP	2.5330	1.504
	ΔLREC	-0.4268	-3.912
	ΔLPG	0.4576	1.986
India	ΔLPEC	2.3000	1.576
	ΔLGDP	0.0665	0.0460
	ΔLREC	0.3333	0.3293
	ΔLPG	0.3566	0.5486
Malaysia	ΔLPEC	1.0230	3.303
	ΔLGDP	-0.0577	-0.1672
	ΔLREC	0.0572	1.012
	ΔLPG	-0.0565	-0.2874
Mexico	ΔLPEC	-1.1960	-1.286
	ΔLGDP	-0.2015	-0.3337
	ΔLREC	0.2119	0.4066
	ΔLPG	0.4048	1.403
Morocco	ΔLPEC	0.9477	2.132
	ΔLGDP	0.6559	1.665
	ΔLREC	-0.1993	2.225
	ΔLPG	-0.2347	-1.269
Egypt	ΔLPEC	-0.4595	-1.415
	ΔLGDP	0.7890	2.888
	ΔLREC	-1.1930	-5.278
	ΔLPG	0.5356	3.535

Country	Variable	Beta	t-stat
South Africa	ΔLPEC	0.8626	0.4824
	ΔLGDP	-0.0143	-0.0102
	ΔLREC	0.0010	0.0025
	ΔLPG	0.0468	0.2789
Thailand	ΔLPEC	-0.2410	-1.172
	ΔLGDP	0.6075	2.593
	ΔLREC	-0.4471	-5.611
	ΔLPG	0.3305	3.472
Turkey	ΔLPEC	1.3870	4.686
	ΔLGDP	-0.3400	-1.233
	ΔLREC	-0.3341	-1.860
	ΔLPG	0.1194	1.129
China	ΔLPEC	-2.1100	-1.906
	ΔLGDP	0.0301	0.0224
	ΔLREC	-2.8720	-3.400
	ΔLPG	-0.1307	-1.898

Table 15. Country-Specific DOLSMG Long-Run Estimation Results (High-Income Countries)
This table reports country-specific DOLSMG long-run estimates for the high-income economies. It highlights cross-country variation in the long-run effects of energy use and renewables on CO_2 emissions.

Country	Variable	Beta	t-stat
Australia	ΔLPEC	-.03273	-.04914
	ΔLGDP	.6288	1.339
	ΔLREC	-.1146	-1.54
	ΔLPG	.1846	1.722
Belgium	ΔLPEC	-.2836	-1.098
	ΔLGDP	2.183	4.056
	ΔLREC	-.2309	-6.122
	ΔLPG	-.05582	-.7578
Canada	ΔLPEC	-.01166	-.04089
	ΔLGDP	.3852	1.124
	ΔLREC	-.1678	-1.531
	ΔLPG	-.01825	-.2456
Chile	ΔLPEC	2.436	2.102
	ΔLGDP	-.897	-1.196
	ΔLREC	.7382	2.108
	ΔLPG	.5341	1.72
Finland	ΔLPEC	-1.15	-1.427
	ΔLGDP	-.3964	-.4454
	ΔLREC	.449	2.364
	ΔLPG	.6273	4.782
France	ΔLPEC	1.674	5.117
	ΔLGDP	-.01411	-.04752
	ΔLREC	-.06126	-1.088
	ΔLPG	-.06585	-2.963

Country	Variable	Beta	t-stat
Germany	ΔLPEC	1.034	1.6
	ΔLGDP	-.001549	-.004442
	ΔLREC	-.46	-1.609
	ΔLPG	-.3368	-4.378
Greece	ΔLPEC	1.554	4.511
	ΔLGDP	-.3745	-.7383
	ΔLREC	-.05129	-.5425
	ΔLPG	.003863	.01897
Hungary	ΔLPEC	.4749	1.858
	ΔLGDP	-.03021	-.2117
	ΔLREC	-.2389	-3.816
	ΔLPG	.1746	2.48
Ireland	ΔLPEC	-1.497	-2.274
	ΔLGDP	1.213	3.279
	ΔLREC	-.3806	-2.789
	ΔLPG	.142	.5508
Japan	ΔLPEC	-.9132	-1.761
	ΔLGDP	.2252	.2485
	ΔLREC	-.09912	-.3985
	ΔLPG	.03632	.2502
New Zealand	ΔLPEC	1.124	4.702
	ΔLGDP	-.1472	-.8853
	ΔLREC	-.7913	-6.481
	ΔLPG	-.3895	-4.035
Russia	ΔLPEC	.8187	5.09
	ΔLGDP	-.05426	-.2421
	ΔLREC	-.4636	-7.666
	ΔLPG	.01101	.3329
Spain	ΔLPEC	2.541	3.949
	ΔLGDP	-1.426	-2.078
	ΔLREC	.3584	1.601
	ΔLPG	.1334	.8875
USA	ΔLPEC	2.282	2.193
	ΔLGDP	-.5943	-.9824
	ΔLREC	-1.135	-3.923
	ΔLPG	.5756	2.004