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Causal Relationship Between GDP and Carbon Emissions: Panel Data Analysis for Türkiye and OECD Countries

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Abstract   In this study, by using data from 14 OECD countries between 1990-2023 years, I analyze the impact of per capita gross domestic product (GDP), per capita energy consumption (EC), and the share of the industrial sector in the economy (IND) on carbon dioxide (CO_2) emissions. The analysis contains the cross-sectional dependence between the series that was determined with the aid of the CD test improved by Pesaran (2004). Then, the second-generation unit root tests, IPS (2003) and CADF (2007), were applied, and it was concluded that all variables were stationary in their first differences [I(1)]. In this particular context, the ARDL methodology was employed to compare the Pooled Mean Group (PMG), Mean Group (MG), and Dynamic Fixed Effects (DFE) forecasters, and the Hausman test results indicated that the PMG estimator was the most suitable model for forecaster. The results show that, eventually, GDP has a statistically important negative impact on CO_2 emissions, even though both EC and IND variables exert statistically important positive impact on CO_2 emissions over the same period of time. The short-run coefficients at the country level signify heterogeneity in how variations in energy consumption and the industrial sector's share influence carbon emissions. For this reason, it is clear that policymakers should prioritise supporting tools to increase energy efficiency, focusing on low-carbon renewable energy technologies in industry, and supporting green investments in this regard.

Keywords   CO2 Emissions · Economic Growth · Panel ARDL Method

Jel Codes   C12, O44, Q54.

Causal Relationship Between GDP and Carbon Emissions: Panel Data Analysis for Türkiye and OECD Countries

Climate change isn't just the most important issue of this century; it's also a major focus on countries' economic structures and sustainable development policies. Carbon dioxide (CO_2) emissions, energy consumption, and industrial activity are the most significant factors at the heart of this agenda. With the acceleration of industrialization since the 1990s, environmental pollution has increased, and the relationship between the environment and economic growth has gained greater significance at the global level. Although measuring this relationship is not easy, in 1955, Simon Kuznets developed a theoretical base, namely the "Kuznets Curve," to describe the relationship between income distribution and economic growth. However, his original approach was considered insufficient and expanded by adding ecological dimensions in the 1990s, which is named 'Environmental Kuznets Curve (EKC)'. The ECF hypothesis indicates that there is a systematic affair between economic growth and environmental grade; environmental degradation rises in the early stages of development but tends to decrease once a certain income threshold is attained (Grossman and Krueger, 1991).

OECD countries, by high economic growth rates, energy consumption, and industrial activities, are leaders in contributing to global carbon emissions. The selection of 14 OECD countries for this study was based on the availability of long-term data (1990–2023) and the significant differences they exhibit in terms of income levels, energy consumption patterns, and environmental policies. These characteristics are necessary to test the Environmental Kuznets Curve hypothesis within the OECD framework. However, this not only boosted production and income but also created a great impact on the environment. The main negative effects are environmental pollution, decrease of natural resources, and derangement of ecological balance. Thus, creating a new growth model that regards the sustainability of natural resources while reducing the negative impact on development and social welfare is unavoidable

The sustainable development concept emphasizes that economic progress should be underpinned not only by heightened production and revenue but also by environmentally precise legislation, energy-efficient practices, and the productive utilization of resources. In this regard, clean, renewable energy and productive use of energy resources are considered perfect alternatives that accelerate economic development while decreasing environmental cost. Policies that decrease carbon emissions, increase energy efficiency and promote green technologies are key elements of sustainable growth concept.

In this study, I use data from 1990 to 2023 to investigate the short- and long-term effects of per capita gross domestic product (GDP), energy consumption (EC) and the industrial sector's share of the economy (IND) on per capita CO_2 emissions in 14 OECD countries by employing The Panel ARDL method. The findings intent to inform policy designs that improve energy efficiency, speed up the clean energy transition, and encourage decarbonisation in the industrial sector. Thus, the study aims to fill the existing gap in the literature and provides empirical evidence that sustainable economic growth is possible within the framework of environmental adaptation.

Literature

A substantial body of research has explored the relationship between economic growth, energy consumption, and carbon emissions in the existing literature. An examination of the literature in Table 1 shows that these relationships have been investigated using many different methods in different countries and at different times, yielding contradictory findings.

Table 1

Literature Review

Author of the Study	Year	Industry / Company and Period	Method	Variables	Outcome of the Study
Akın et al.	2024	G-7 countries 2000-2019	Panel Causality Test	Migration, GDP, Carbon Dioxide (CO2)	The study examined G7 economies using causality analysis and shows that there is a one-way relationship from emigration to carbon emissions, from economic growth to carbon emissions, and again from economic growth to emigration in these countries.
Özman and Karadaş	2023	BRICS-T Countries 2000-2019	Toda-Yamamoto Analysis.	Energy consumption, economic growth, and carbon emissions	The study showed that there is a unidirectional causality between GDP per capita and renewable energy use towards CO_2 emissions per capita in the causality analysis, and according to the cointegration results, GDP per capita increases emissions while renewable energy use decreases emissions.
Kazanasmaz et al.	2023	Turkey 1967-2017	Granger Causality and Johansen Cointegration Tests	GDP, carbon dioxide (CO2)	In the study conducted on Türkiye, it was concluded that while electricity consumption positively affects economic growth in the long term, carbon dioxide emissions negatively affect economic growth in the same period.
Özel & Ekiz	2021	Turkey 1998-2015	Granger causality tests	GDP, carbon dioxide (CO2) and Energy Consumption	The study demonstrated the existence of a long-term relationship between the variables and demonstrated that increases in CO_2 emissions and energy consumption had a significant and positive impact on economic growth in Türkiye during the examined time period. Furthermore, it was determined that the increase in CO_2 emissions contributed 0.93% to economic consumption, while the change in energy consumption had a positive impact of 0.19%.
Atgür	2021	China 1971-2014	Johansen Cointegration Test	GDP, CO2 and Energy Consumption	The study found that economic growth and energy consumption have a significant effect on carbon emissions. It was also suggested that there is a positive relationship between economic growth and energy consumption.
Yılmaz and Dilber	2020	Turkey 1970-2014	ARDL Bounds Test	GDP, Energy Consumption, Foreign Trade Deficit, and CO2	According to the ARDL bounds test results, a 1% increase in electricity consumption, a 0.15% increase in GDP, and a 0.17% increase in foreign

Author of the Study	Year	Industry / Company and Period	Method	Variables	Outcome of the Study
					trade deficit increase carbon dioxide emissions by 0.15%, 0.60%, and 0.17%, respectively.
Ahmad et al.	2019	China 2000-2016	STIRPAT model	GDP, Carbon Dioxide and Energy Consumption	They have identified a long-term relationship between energy consumption, gross domestic product, urbanization, the construction sector, and carbon emissions.
Sever &İğdeli	2018	Emerging market economies 1990-2014	ARDL Limit Test	GDP, Carbon Dioxide (CO2) and Energy Consumption	The study emphasizes the negative impact of carbon dioxide emissions on gross domestic product in the long term, while energy consumption has a positive impact on gross domestic product.
Aye & Edoja	2017	31 Countries	Dynamic Panel method	GDP, CO2 and Energy Consumption	The results of the studies show that carbon emissions were positively affected during periods of high economic growth.
Xiongling	2016	China 1961-2010	Cointegration Analysis	GDP, Carbon Dioxide (CO2)	The results reveal a one-way causal linkage running from the GDP variable to the carbon emissions variable over the long term.
Topallı	2016	India, China, South Africa, Brazil 1980-2010	Panel Causality Analysis	CO2, Economic Growth	The results of the analysis, when evaluated in the short and long term, reveal a unidirectional causal relationship running from economic growth to CO_2 emissions. This result suggests that production and income growth in the Turkish economy increase environmental pressure, triggering carbon emissions. In other words, it can be argued that economic growth increases environmental pollution through energy consumption and industrial activities, and therefore, growth imposes environmental costs.
Tay& Yurtkur	2016	Turkey 1960 2010	Cointegration Analysis	CO2, Economic Growth	The analysis results indicate a non-linear relationship between CO_2 emissions and economic growth. This finding suggests that economic economies experience increased temperature deterioration up to a certain level of growth, but after a certain level of stability, economic development appears to have no negative environmental impact.
Kasperowicz	2015	18 EU Member States 1995 2012	Panel Data Analysis	CO2, Economic Growth	The analyses in the study identified an inverse relationship between economic growth and carbon emissions in the long run, indicating that the effects on the economy continue to strengthen over time and that the effect of sustainable growth will continue to be effective.
Arouri et al.	2014	16 African countries 1988-2010	Panel Granger	GDP and Energy Consumption	The research highlights that there is a negative relationship between GDP and carbon dioxide

Author of the Study	Year	Industry / Company and Period	Method	Variables	Outcome of the Study
			causality test		emissions, and also suggests that there may be a link between energy consumption and GDP.
Bozkurt & Akan	2014	Turkey 1960 2010	Johansen Cointegration Analysis	GDP, CO2and Energy Consumption	A study examining the interaction between carbon emissions, gross domestic product (GDP), and energy consumption suggested that increased carbon emissions have a negative impact on economic growth. Conversely, carbon emissions were found to have a positive and significant impact on energy consumption.
Farhani & Jaleleddine	2012	MENA Region 1973-2008	Panel Data Analysis	GDP, Carbon Dioxide (CO2) and Energy Consumption	The study analyzed the relationship between carbon emissions, gross domestic product (GDP), and energy consumption and found that GDP and CO_2 emissions affect energy consumption, leading to increased energy use leading to increases in both income levels and carbon emissions.
Saboori et al.	2012	Malaysia 1980 2009	ARDL Limit Test	GDP, CO2	The research examined whether there was a significant relationship between CO_2 emissions and economic growth in the short and long term, and revealed the effects of stress on the increase in economic activity, energy consumption and production intensity.
Şahbaz et al.	2012	Turkey 1970-2010	Granger causality approach	GDP, CO2 and Energy Consumption	The research emphasized the increasing effect of economic growth on CO_2 emissions along with energy intensity and globalization processes.
Pao & Tsai	2011	Brazil 1980-2007	Grey prediction model (GM)	GDP, Carbon Dioxide (CO2)	Causality analysis was conducted in the research and it was revealed that there is a strong two-way causal relationship between income, energy consumption and carbon emissions.
Hossain	2011	Newly Industrialized Countries 1971 2007	Panel Cointegration Method	CO2, Energy Consumption, Economic Growth	In the research analysis, a short-term mutual causality relationship was identified between the variables and the dynamic nature of the distance between them was discussed, emphasizing that the variables are constantly changing.
Jaunky	2011	In 36 High Income countries 1980-2005	Cointegration tests	CO2, Energy Consumption, Economic Growth	The study demonstrated a unidirectional causal relationship between GDP and CO_2 emissions in both the short and long term, emphasizing that economic growth plays a direct role in these effects. In terms of coefficients, a 1% increase in GDP increased CO_2 emissions by approximately 0.68% in the short term and approximately 0.22% in the long term.
Öztürk & Acaravcı	2010	Turkey 1968 2005	ARDL Limit Test	CO2, Energy Consumption,	The study found that long-term CO_2 emissions are affected by changes in energy consumption,

Author of the Study	Year	Industry / Company and Period	Method	Variables	Outcome of the Study
				Economic Growth, Employment	economic growth and employment levels, and that there is a positive relationship between GDP and CO_2 emissions.
Azomahou & Phu	2001	5 South Asian countries 1980-2010	Panel Cointegration Method	CO2, Energy Consumption	The results of the research analysis found that energy consumption and CO_2 emissions have a significant effect on economic growth.This, in turn, plays an expanding role in sustainable energy production and stimulates economic activity. Furthermore, a 1% increase in CO_2 emissions contributes 0.17% to the overall economic impact.

Although the relationship between economic growth, energy consumption and carbon emissions has been addressed in various countries and methods in the reviewed literature, it has been observed that the majority of the evaluated studies, and even a significant part of them, have been evaluated on a single country basis (Öztürk and Acaravcı, 2010; Saboori et al., 2012; Bozkurt and Akan, 2014; Xiongling, 2016; Tay and Yurtkur, 2016; Özel and Ekiz, 2021; Kazanasmaz et al., 2023) and the studies on large country groups have focused on long-term relationships (Hossain, 2011; Arouri et al. 2014; Aye & Edoja, 2017; Destek et al., 2020; Sever & İğdeli, 2018; Akın et al., 2024). But, it is noteworthy that research that directly adds the share of the industrial sector in the economy to the model is limited and that comprehensive studies examining both short-term and long-term relationships simultaneously in OECD countries are lacking. By employing the Panel ARDL approach to capture both short- and long-term dynamics, this study empirically investigates the impact of the industrial sector on carbon emissions using an extensive panel dataset covering 14 OECD countries for the period from 1990 to 2023, thereby providing a distinctive contribution that addresses an existing gap in the literature.

Data and Methodology

The main objective of this study is to evaluate the short and long term impact of per capita gross domestic product (GDP), per capita energy consumption (EC) and the share of the industrial sector in the economy (IND) on per capita carbon emissions (CO_2) in 14 OECD countries. The countries evaluated in the study are Türkiye, Germany, France, Italy, Spain, the United States, the United Kingdom, Canada, Austria, Japan, Poland, the Netherlands, Sweden, and Mexico, and are examined with annual data covering the years 1990 to 2023. Furthermore, the panel data structure has both a time dimension of T = 34 and a cross-sectional dimension of N = 14, allowing for the simultaneous analysis of long term relationships and short term dynamics. Under this heading, the research model, the variables used and the econometric methods applied are explained in detail and the equation of the model is given in Equation 1.

$$CO_{i,t}^2 = \alpha_i + \beta_1 GDP_{i,t} + \beta_2 EC_{i,t} + \beta_3 IND_{i,t} + \varepsilon_{i,t} \tag{1}$$

The i in the equation represents the cross-sectional unit of the panel data and includes 14 OECD countries (i=1,..14) and t represents the time dimension and shows the 34-year observation between 1990-2023 (t=1990-2023). α represents the model's constant term; ε represents the error terms; β_i (i = 1, 2, 3) represents the coefficients indicating the effects of the independent variables on the dependent variable. The definitions of the variables included in the research model are presented in Table 2.

Table 2

Variable Definitions

Symbol	Variable
CO^2	Annual carbon emissions per capita
GDP	Annual gross domestic product per capita
EC	Annual energy consumption per capita
IND	Share of the industrial sector in the economy

The variables defined in Table 2 were compiled using annual data from 14 OECD countries for the period 1990-2023, creating a panel data set. Due to the long time dimension (T>30), it is necessary to test the stationarity levels of the variables to avoid the risk of spurious regression that may arise from stationarity in the series (Sohag, Umar, & Alam, 2018). However, in order to select the appropriate unit root test, cross-sectional dependence between variables must first be tested.This is because first-generation unit root tests yield inconsistent results under cross-sectional dependence, while second-generation tests have been developed to be more robust to this situation (Tatoğlu, 2018, p. 68). In this context, the CD cross-sectional dependence test developed by Pesaran (2004) was applied in the study. The findings indicated that cross-sectional dependence existed across all variables. In this direction, the second generation unit root tests, Extended Im, Pesaran and Shin (CADF, 2007) and Im, Pesaran and Shin (IPS, 2003) tests, were used to examine the stationarity properties of the series (Im and Pesaran, 2003; Levin, Lin and Chu, 2002; Pesaran, 2007).According to the results of unit root tests (second generation), it was observed that the variables were not stationary at the level values and it was determined that they became stationary when their first differences were taken (I(1)). Due to the suspicion of spurious regression in the regression analyses conducted with variables that were not stationary at the level, the research model was estimated using the Panel ARDL approach.

The Panel ARDL model is a dynamic estimation method developed for panel data models with large T and large N characteristics, resistant to heterogeneity and cross-sectional dependence. The method allows coefficient estimation for the panel sample based on unit-specific ARDL model findings. The ARDL model in its panel form is represented in Equation (2) below (Blackburne & Frank, 2007).

$$y_{i,t} = \sum_{j=1}^{p} \lambda_{i,j} y_{i,t-j} + \sum_{j=0}^{q} \delta'_{i,j} X_{i,t-j} + \mu_i + \varepsilon_{i,t} \tag{2}$$

Here, the expression i=1,2,...,N represents the units, while t=1,2,...,T represents the time periods. $y_{(i,t)}$ denotes the dependent variable, $y_{(i,t-j)}$ denotes the lagged values of this variable, and $\lambda_{(i,j)}$ denotes the coefficients associated with these lagged values. $X_{(i,t)}$ represents kX1 dimensional explanatory variable vector, while $\delta'_{i,j}$ denotes the vector of coefficients corresponding to these explanatory variables. μ_i represents the unit-specific effects, $\varepsilon_{i,t}$ represents the error terms for unit i at time t. For ARDL model estimation in panel data, the number of observations in the time dimension for units must be sufficient to estimate a separate ARDL model for each unit.

If the variables in Equation 1 are I(1) and integrated, a property of the cointegration procedure is that the error terms are expected to be an I(0) series. This property implies an error-correcting model in which the short-term dynamics of the variables in the system are affected by deviations from equilibrium. Therefore, Equation 1 can be rewritten in error-correcting form as Equation 3.

$$\Delta y_{i,t} = \varnothing_i\left(y_{i,t-1} - \theta_i' X_{i,t}\right) + \sum_{j=1}^{p-1} \lambda_{i,j}^* \Delta y_{i,t-1} + \sum_{j=0}^{q-1} \delta_{i,j}'^* \Delta X_{i,t-j} + \mu_i + \varepsilon_{i,t} \qquad (3)$$

Equation 3: $\varnothing_i = -(1 - \sum_{j=1}^{p} \lambda_{i,j})$, $\theta_i = \sum_{j=0}^{q} \delta_{i,j}/(1 - k \sum_k \lambda_{i,k})$, $\lambda_{i,j}^* = -\sum_{m=j+1}^{q} \lambda_{i,m}$, *j=1,2,…,p-1* and $\delta_{i,j}^* = -\sum_{m=j+1}^{q} \delta_{i,m}$, *j=1,2,…,q-1*. $\varnothing_i$ is the error correction term, also referred to as the adaptation term. The $\varnothing_i$ parameter must be meaningful and negative when the variables show a return to long-term equilibrium. When this condition is met, it can be said that the long-term relationships between the variables are meaningful.

Three basic estimation methods were employed in the estimation period of the panel ARDL model, Dynamic Fixed Effects (DFE), Pooled Mean Group (PMG), and Mean Group (MG). The DFE approach body time-series data from all cross-sectional units in the panel into a single, combined model, allowing just the intercept to vary across units. Contrary to the MG estimator estimates the model individually for each cross-sectional unit and takes the simple arithmetic average of the resulting coefficients. This approach allows for heterogeneity across units in terms of constant terms, error variances, and declivity quotients (Pesaran and Smith, 1995). The PMG estimator combines the strengths of both the DFE and MG methods, creating a hybrid approach. It supposes that long-term coefficients are homogeneous across units while recognizing that short-term dynamics and error terms can alter across groups (Pesaran, Shin, and Smith, 1997).

In panel ARDL analysis, the Hausman test is usually used to choose between the PMG (Pooled Mean Group) and MG (Mean Group) estimators in the first step. If the test consequences remark that the PMG estimator is effective, it is considered the proper method for the model. Although, if the test consequences propose that the MG estimator performs better, the second step comprises comparing the MG and DFE (Dynamic Fixed Effects) estimators to identify which one supplies the most accurate and effective results (Blackburne and Frank, 2007).

This method is of critical importance, primarily in testing the long-term persistence of homogeneity in panel data sets. Researchers use the Hausman test to assess how unit-based differences are reflected in the model and to create the most appropriate estimation lens for the data characteristics and the purpose of the analysis. This comprehensive analysis method is a complementary test that increases the accuracy, spread, and interpretative power of the panel ARDL model.

Table 3

OECD Countries Used in the Study

Country Name	Country Name	Country Name
Turkey	Germany	France
Italy	Spain	United States
United Kingdom	Canada	Austria
Japan	Poland	Netherlands
Sweden	Mexico	

The data set of 14 OECD countries evaluated in the study was handled annually for the periods 1990-2023.

Findings

Descriptive statistics of the variables included in the research model, normality test findings and Pesaran (2004) cross-sectional dependency (CD) test results are shown comprehensively in Table 4.

Table 4

Descriptive Statistics and Pre-Tests

| Variables	CO²	GDP	EC	IND
Average	9.396	30821.370	4009.771	25.208
Std. Deviation	4.745	16559.360	1909.297	4.636
Min.	2.675	1731.210	887.163	16.088
Max.	21.013	82304.620	8422.733	34.848
S-K Test	$\chi^2_{(2)}=36.30$*** [0.000]	$\chi^2_{(2)}=18.08$*** [0.000]	$\chi^2_{(2)}=25.54$*** [0.000]	$\chi^2_{(2)}=27.65$*** [0.000]
Pesaran (2004) CD Test	CD=24.00*** [0.000]	CD=47.51*** [0.000]	CD=20.04*** [0.000]	CD=28.01*** [0.000]
Number of Observations	476	476	476	476

*** (%1), ** (%5), * (%10) indicate statistical significance levels. χ^2 represents the test statistic, the degrees of freedom are indicated in parentheses, and the values in square brackets show the significance levels of the tests.

The minimum value of the CO_2 variable was 2.675 and the maximum value was found to be 21.013. The mean of the variable is calculated as 9.396, and the standard deviation is 4.745 ($\chi^2(2)=36.30$, $p<0.01$). It also shows cross-sectional dependence at a 1% significance level (CD=24.00, $p<0.01$). Similarly, the GDP variable does not follow a normal distribution and ranges from 1,731.210 to 82,304.620. The mean value of GDP was found to be 30,821.370, and this variable was also found to exhibit significant cross-sectional dependence at the 1% level ($\chi^2(2)=18.08$, $p<0.01$; CD=47.51, $p<0.01$). The minimum and maximum values for the EC variable are 887.163 and 8,422.733, respectively; the mean is 4,009.771 and the standard deviation is 1,909.297 ($\chi^2(2)=25.54$, $p<0.01$). The EC variable also shows cross-sectional dependence at the 1% significance level (CD=20.04, $p<0.01$). Similarly, the IND variable ranges from 16.088 to 34.848, with a mean value of 25.208 and a standard deviation of 4.636 ($\chi^2(2)=27.65$, $p<0.01$). This variable also exhibits cross-sectional dependence at the 1% significance level (CD=28.01, $p<0.01$). The time series graphs for the variables are as shown in Figure 1.

Figure 1

Variable Time Course Graphs
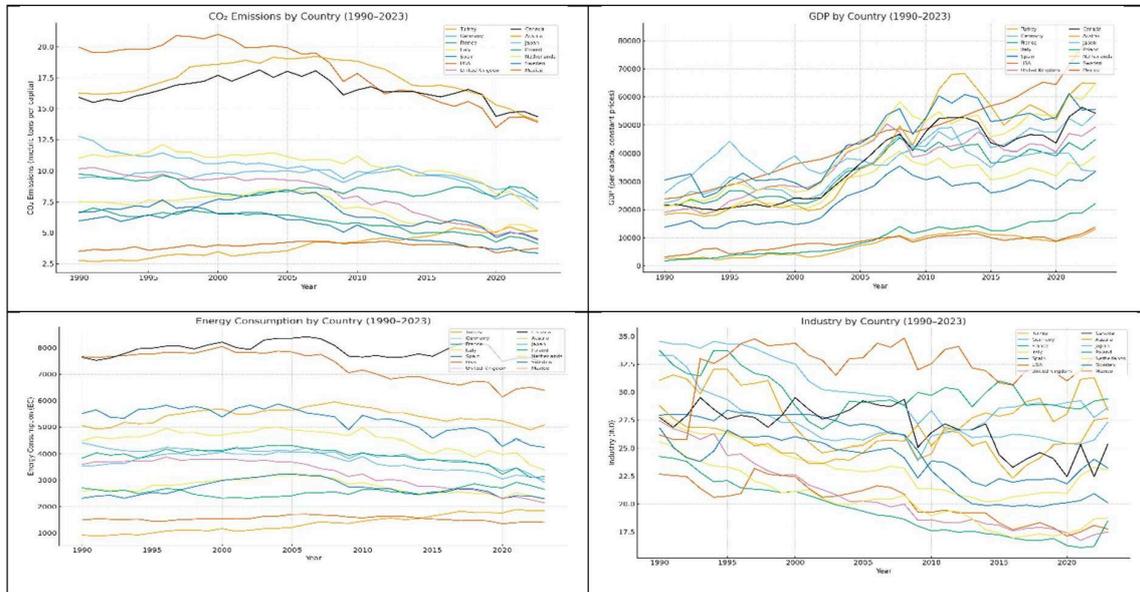
When examining the graphs, the upward divergence of countries such as the US, Austria, and Canada in terms of CO2 values is noteworthy. Turkey and Mexico, on the other hand, diverge downward from other OECD countries in terms of CO2 values. Countries that diverge upward in terms of GDP are generally those with high CO2 values, such as Japan. This pattern is quite similar for the EC variable. In terms of the IND variable, the dynamics appear to be quite variable at the beginning and end of the study period. Countries with high IND values in the 1990s are observed to have lower IND values after 2000.

To determine the stability levels of the variables, the findings obtained from the IPS (2003) and CADF (2007) tests, which are second-generation unit root tests providing reliable results under cross-sectional dependence, are presented in Table 5.

Table 5

Second Generation Unit Root Test Findings

Variables	IPS (2003)		CADF (2007)		Decision
	Fixed	**Fixed + Trend**	**Fixed**	**Fixed + Trend**	
CO^2	2.239	2.324	−1.419	−2.360	I(1)
	0.987	0.989	0.919	0.467	
ΔCO^2	−15.932***	−14.722***	−5.334***	−5.515***	
	0.000	0.000	0.000	0.000	
GDP	1.481	−0.253	−2.045	−2.317	I(1)
	0.931	0.400	0.137	0.538	
Δ GDP	−14.224***	−12.193***	−2.783***	−2.848**	
	0.000	0.000	0.000	0.015	
EC	2.231	−0.896	−1.167	−1.827	I(1)
	0.987	0.185	0.992	0.985	
Δ EC	−19.595***	−19.771*	−2.404***	−2.757**	

| Variables	IPS (2003)		CADF (2007)		Decision
	Fixed	Fixed + Trend	Fixed	Fixed + Trend	
	0.000	0.000	0.006	0.038	
IND	−2.202*	−0.116	−1.782	−1.612	
	0.014	0.454	0.481	0.999	I(1)
Δ IND	−16.989***	−15.335***	−2.302**	−3.058***	
	0.000	0.000	0.017	0.000	

*** (%1), ** (%5), * (%1) symbolize significance at the significance level, [square brackets contain test significance values.]

According to the findings in Table 5, the results of the second-generation panel unit root tests (IPS (2003) and CADF (2007) reveal that all variables used in the research model are non-stationary at their level values. In other words, it was observed that the mean and variance of the series at their level did not remain constant over time, and therefore, they were affected by random fluctuations. However, when the first differences of the variables were taken, the series became stationary and were statistically free of the unit root problem. This indicates that all variables are integrated of the first order (I(1)). This result from the stationarity analysis indicates that the model may be at risk of spurious regression and therefore requires careful selection of the appropriate econometric method. In this context, the Panel ARDL model was preferred because the variables have the same degree of integration, allowing for the joint analysis of both short- and long-term relationships.

Scatter plots are presented in Figure 2 to examine the correlation structures between the variables prior to the Panel ARDL model estimation. A statistically significant yet weak to moderate positive relationship is observed between the CO_2 variable and the GDP variable at the 1% significance level (R=0.349, p<0.01). When examining the scatter plot, it is seen that countries with low CO2 values, such as Turkey, Mexico, and relatively Spain, also have low GDP values, while countries such as the USA, Canada, and Austria stand out from other countries in terms of high CO2 and high GDP values.

Figure 2

Variable Time Course Graphs
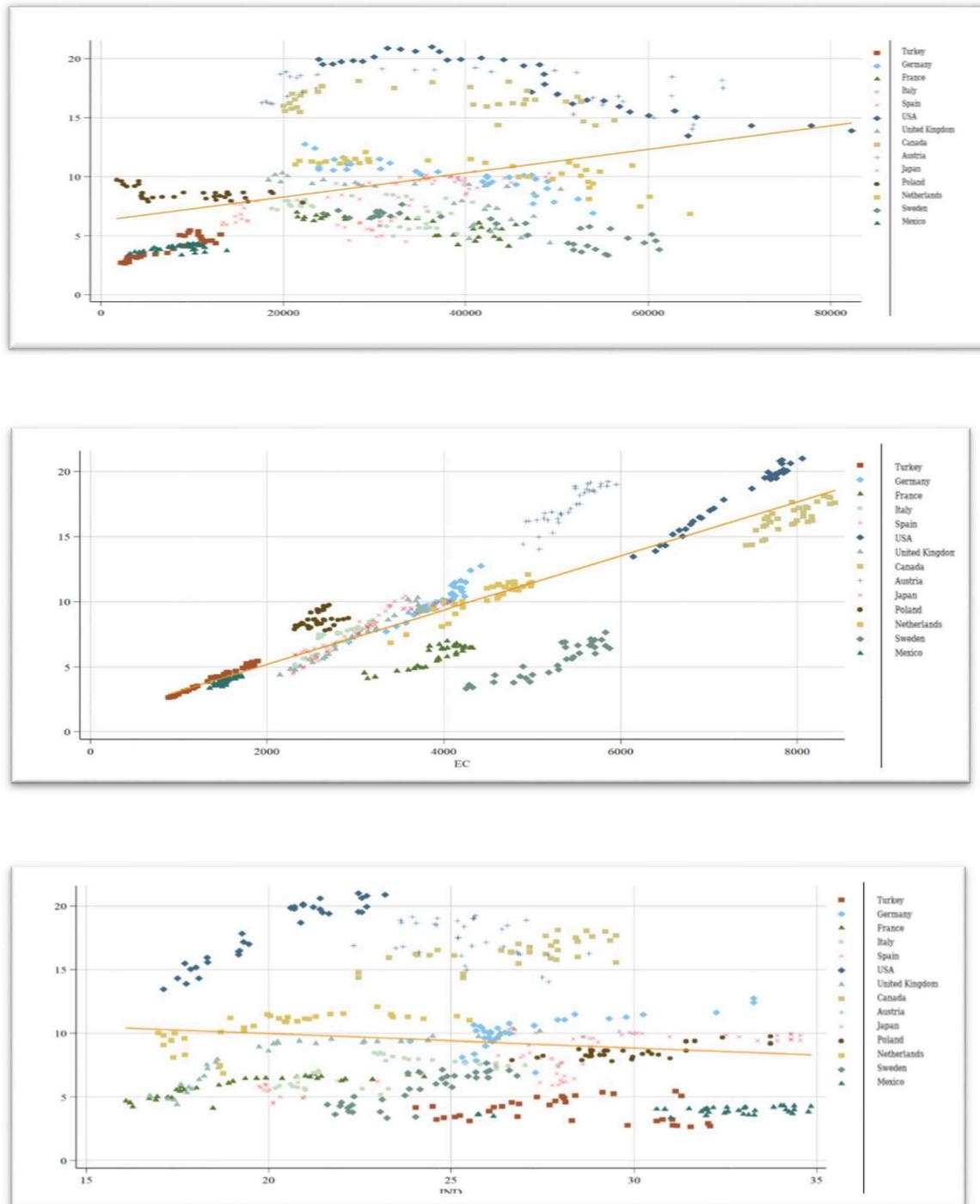
There is a statistically significant and quite strong positive correlation between the EC variable and the CO_2 variable at a 1% significance level (R=0.836, p<0.01). Countries with high EC values, such as the USA and Canada, also have high CO2 values, while countries with low EC values, such as Turkey and Mexico, have low CO2 values. At the 5% significance level, a statistically significant but weak negative correlation is

observed between the IND variable and the CO_2 variable (R=-0.107, p<0.05). Examining the graph, it is seen that countries with medium IND values, such as Austria and Canada, have high CO2 values.

In estimating the panel ARDL model, models with up to two lags were evaluated in terms of the Akaike Information Criterion (AIC) and the error correction term (ECTt-1) to determine the most appropriate lag lengths. It was observed that the condition of the error correction term being statistically significant and negative was met in models where the dependent variable had a one-period lag. Accordingly, the AIC values for different lag lengths of the independent variables were compared, and it was decided to determine the most appropriate lag structure based on this. Comparisons regarding the lag criteria are presented in Table 4.

Table 6
Table 6: Panel ARDL Model Lag Selection

ARDL(q, p_1, p_2, p_1) Model	AIC	ECT$_{t-1}$
ARDL(1, 1, 1, 1)	−353.499	−0.062***
ARDL(1, 2, 1, 1)	−357.834	−0.080***
ARDL(1, 1, 2, 1)	−353.169	−0.133***
ARDL(1, 1, 1, 2)	−349.666	−0.070***
ARDL(1, 2, 2, 1)	−371.230	−0.140***
ARDL(1, 2, 1, 2)	−379.570	−0.091***
ARDL(1, 1, 2, 2)	−372.560	−0.153***
ARDL(1, 2, 2, 2)	−401.363	−0.159***

*** (1%), ** (5%), * (1%) indicates significance at the significance level.

Table 6 shows that among the models where the dependent variable has a single lag, the model with independent variables having two lags each has the lowest AIC value, indicating that my error correction term satisfies the necessary conditions. In this case, the optimal model can be said to be the ARDL(1, 2, 2, 2) model. The specification tests, diagnostic statistics, and estimation results for the ARDL(1, 2, 2, 2) model are as shown in Table 7.

Table 7
ARDL (1, 2, 2, 2) Model Estimates

Panel 1: Long-Term Coefficients			
	PMG	MG	DFE
GDP	−0.000041***	−0.000024*	−0.000071***
	0.000008	0.000015	0.000015
	−4.98 [0.000]	−1.68 [0.093]	−4.66 [0.000]
EC	0.003187***	0.002550***	0.002952
	0.000141	0.000272	0.000310
	22.53 [0.000]	9.39 [0.000]	9.53 [0.000]
IND	0.038569*	0.002295	−0.072561
	0.021342	0.041796	0.056116
	1.81 [0.071]	0.05 [0.956]	−1.29 [0.196]
Panel 2: Findings on Short-Term Coefficients and Error Correction Models			
	PMG	MG	DFE

	−0.159010***	−0.314277***	−0.132826***
ECT$_{t-1}$	0.035211	0.040112	0.026333
	−4.52 [0.000]	−7.83 [0.000]	−5.04 [0.000]
	0.000012	0.000017**	0.000013**
ΔGDP$_t$	0.000008	0.000007	0.000006
	1.48 [0.139]	2.43 [0.015]	2.06 [0.039]
	−0.000004	−0.000006	−0.000005
ΔGDP$_{t-1}$	0.000007	0.000007	0.000004
	−0.48 [0.630]	−0.94 [0.349]	−1.04 [0.300]
	0.001475***	0.001359***	0.001253***
ΔEC$_t$	0.000262	0.000281	0.000178
	5.62 [0.000]	4.83 [0.000]	7.05 [0.000]
	0.000002	−0.000063	0.000073
ΔEC$_{t-1}$	0.000113	0.000099	0.000099
	0.02 [0.985]	−0.64 [0.525]	0.74 [0.462]
	−0.019278	−0.032482	0.020948
ΔIND$_t$	0.034940	0.034279	0.019813
	−0.55 [0.581]	−0.95 [0.343]	1.06 [0.290]
	0.045659*	0.050837**	0.006482
ΔIND$_{t-1}$	0.023448	0.024116	0.013496
	1.95 [0.052]	2.11 [0.035]	0.48 [0.631]
Panel 3: Diagnostic Statistics			
Pesaran CD Horizontal Cross-SectionalTest	$\chi^2_{(3)}$=1.756*[0.079]		
Swamy S Heterojenlik Test	$\chi^2_{(52)}$=36085.29***[0.000]		
Hausman Test1 (MG, PMG)	$\chi^2_{(3)}$=0.000 [1.000]		
Hausman Test 2 (MG, DFE)	$\chi^2_{(3)}$=0.000 [1.000]		

*** (1%), ** (5%), * (1%) indicate significance at the significance level, χ2: Chi-square test statistic.

As seen in Table 7, there is a cross-sectional dependency problem in the model at a significance level of 10% ($\chi^2(3)$=1.756, $p<0.10$). Furthermore, the results of the Swamy S Heterogeneity Test indicate that the model has a heterogeneous structure at the 1% significance level ($\chi^2(52)$=36085.29, $p<0.01$). In the estimation process of the panel ARDL model, Hausman tests were applied to determine the most appropriate estimator among the estimators robust to heterogeneity and cross-sectional dependence. The Hausman test findings revealed that the PMG estimator was effective because the null hypothesis was not rejected ($\chi^2(3)$=0.000, $p>0.10$). Therefore, it was deemed appropriate to estimate the model using the PMG estimator, and no additional Hausman test was required between the MG and DFE estimators.

Analysis of long-term consequences based upon PMG estimates reveals that the GDP variable negatively effects CO_2 emissions. This finding indicates that growing GDP causes a decline in per capita carbon emissions over the long term.

When long term results were examined, the EC variable was found to have a positive effect on the CO_2 variable with β_2=0.003187, $p<0.01$. This finding indicates that carbon emissions increased as a result of the increase in per capita electricity consumption in the panel countries during the period examined. Similarly,

it was determined that the IND variable had a positive relationship with the CO_2 variable as a result of the values of β_3=0.038569, p<0.10, and this finding showed that the share of the industrial sector in the national economy increased, causing more carbon emissions in the long term.

When the short-term coefficients were examined with the values of ECTt-1=-0.15010, p<0.01, it was determined that the error correction term was negative. This demonstrates that the error correction mechanism in the model operates effectively and that short-term deviations from the long-term equilibrium are corrected over time.

The analysis of short-term coefficients indicates that the current period GDP value has no statistically significant effect at the 10% significance level on the CO_2 level for the same period. In contrast, it has been determined that the GDP variable with a one-period lag has a positive effect at the 1% significance level on current period CO_2 emissions. Neither the current nor the lagged values of the EC variable have a significant effect on current period CO_2. On the other hand, the current period IND variable has no significant effect on CO_2 emissions, while the lagged IND variable has a positive effect on current period CO_2.

According to the results obtained from the PMG model, the long-term negative effect of the GDP variable on CO_2 emissions indicates that economic growth in the analyzed countries supports environmental improvement at a certain income level. It can be argued that with increasing levels of economic development, technological innovations, environmentally focused policies, and energy efficiency investments are effective in reducing carbon emissions. Conversely, the long-term positive and highly significant long-term effect of the energy consumption (EC) variable reveals that energy consumption is still largely based on fossil fuels and that the transition to renewable energy has not reached sufficient maturity in all countries. In like manner, the long term positive and significant effect of the IND variable, namely the industrial sector share, indicates that the energy intensive nature of industrial production leads to an increase in carbon emissions. This highlights the importance of accelerating the green transformation in the industrial sector, ensuring the widespread adoption of clean production technologies, and implementing energy efficiency policies.

The table containing the analysis by country for the short term is shared in Appendix 2.When the country-specific short-run coefficients in Annex 2 are examined, it is seen that the error correction term (ECt-1) is negative for most countries, meaning that deviations from the long-run equilibrium largely disappear in the short run. The effect of the GDP variable on CO_2 emissions in the short term shows heterogeneity across countries. Positive and significant effects were observed in France, Poland, the Netherlands, and Mexico, while in some countries this effect was statistically insignificant. The short-term effect of the EC variable was found to be positive and significant in many countries, indicating that increases in electricity/energy consumption tend to increase CO_2 emissions in the short term. The short-term coefficients of the IND variable are significant in a more limited number of countries. In Italy, Spain, and Mexico, a lagged increase in the industrial share positively affected CO_2 emissions, while in France and Italy, an increase in the current industrial share had negative effects. These findings reveal that, in the short term, fluctuations in energy consumption and the industrial sector are particularly decisive for emission dynamics. The long-term coefficients obtained from the ARDL estimation results are shown in Table 8 by country.

Table 8

Long-Term Coefficients by Country

Country	GDP	EC	IND
Turkey	−0.000061***	0.002627***	0.081084
Germany	−0.000017	0.002166***	0.077303
France	−0.000058***	0.004712***	−0.240848***
Italy	−0.000021	0.001394***	0.044163
Spain	−0.000037	0.002508***	0.003719
United States	0.000121	0.002794**	−0.180799
United Kingdom	−0.000023	0.001004	0.334653
Canada	0.000031**	0.002174***	0.010858
Austria	−0.000072***	0.002115***	0.125370**
Japan	0.000021	0.002616***	0.008378
Poland	−0.000009	0.004246***	−0.287629*
Netherlands	−0.000078***	0.003059***	−0.008670
Sweden	−0.000072***	0.001436*	0.035222
Mexico	−0.000064	0.002855***	0.029319

*** (1%), ** (5%), * (1%) indicates significance at the significance level

When the effects of the GDP variable on the CO2 variable in the long term are examined in Table 8, it is seen that a positive effect is observed for Canada, while a negative effect is observed for Turkey, France, Austria, the Netherlands and Sweden. For Germany, Italy, Spain, the United States, the United Kingdom, Japan, Poland, the Netherlands, and Mexico, it can be said that the GDP variable has no statistically significant long-term effect on the CO2 variable. When examining the long-term effects of the EC variable on the CO2 variable, it can be seen that there is a positive effect for all countries except the United Kingdom. When examining the long-term effects of the IND variable on the CO2 variable, it can be seen that there are negative effects for France and Poland, while there is a significant and positive effect for Austria.

Analysis findings show that the impact of industrial activities on energy consumption, economic growth and carbon emissions yields different results on a country basis in the long term. The negative impact of the GDP variable on CO_2 emissions in Turkey, France, Italy, Spain, the United Kingdom, Austria, Poland, the Netherlands, Mexico, and Sweden demonstrates that economic growth in these countries is aligned with environmental sustainability policies. The decline in carbon emissions in these countries can be traceless the significant effects of technological innovations, energy efficiency practices, and investments in green transformations. In contrast with, the positive relationship observed in the US and Canada indicates that environmental policies have had only a limited effect on economic growth. Also, the strong and significant effect of the energy consumption variable (EC) on increasing CO_2 emissions in many countries highlights the direct correlation between energy use and carbon emissions. The industrial sector variable (IND), which represents the share of the industrial sector, had a negative effect in some countries such as France, the US, Poland, and the Netherlands, while showing positive effects in others.

Conclusion

This study analyzed the short- and long-term effects of per capita energy consumption, per capita gross domestic product, and the share of the industrial sector on per capita carbon emissions using data covering the period 1990–2024 for 14 OECD countries, employing the Panel ARDL method. The findings reveal that GDP has a negative impact on CO_2 emissions in the long term. These results show a dramatic change in the long term, in which per capita income has increased while per capita carbon emissions have reduced. The pattern indicates the effects of replacement in old polluting industries with clean energy as well as the increase in service-oriented sectors. Indeed, high-income countries have shown a strong willpower to shift from polluting industrial activities to service-oriented sectors such as software and high-level technology, which eventually has reduced carbon emissions. What's more, the awareness around clean and sustainable environment forces governments to step further to eliminate polluting industries entirely and find alternative solutions such as solar power and wind energy. Correspondingly, the increase in income makes governments more eager for it.

At the same time, it has been determined that energy consumption and industrial activities variables have a positive effect on CO_2 emissions in the long term. This finding asserts that, in the countries covered by the panel, the long-term increase in per capita electricity consumption and the share of the industrial sector in the economy has led to higher carbon emissions. The results of our panel ARDL analysis reveal that increasing per capita income in the long term reduces CO_2 emission intensity, and this is consistent with studies in the literature that have found similar findings (Arouri et al., 2014; Bozkurt & Akan, 2014; Kasperowicz, 2015; Sever & İğdeli, 2018). Conversely, the long-term positive impact of energy consumption is consistent with research demonstrating a strong energy-emissions relationship (Bozkurt & Akan, 2014; Sever & İğdeli, 2018; Özel & Ekiz, 2021; Atgür, 2021). Moreover, by directly incorporating the industry share (IND) variable into the model and evaluating both short- and long-term effects in OECD countries, we fill a gap that has been addressed only slightly in the literature and reinforce the unique contribution of our study.

To drop carbon emissions, policymakers in OECD countries should focus on three key areas. First, they need to decline rely on fossil fuels by promoting renewable energy sources such as solar and wind power. This shift will help lower the carbon intensity associate energy production. Secondly, technological transformation should be supported to increase energy efficiency in the industrial sector, and clean production practices should be expanded to ensure the environmental compatibility of the production structure. Thirdly, environmental sustainability strategies should be placed at the core of economic growth, green financing instruments should be expanded, and market-based regulations such as carbon taxes should be implemented effectively. Within this framework, market-based policies play an extremely important role. For example, carbon taxes can directly account for the environmental impacts of emissions by raising the relative cost of carbon-intensive production. Mechanisms such as emissions trading schemes (ETS) — for example, cap-and-trade applications — can provide economic incentives for companies to reduce emissions through technological innovations and cleaner production methods. The effective implementation of such tools has the potential to significantly improve the environmental outcomes of economic development in OECD countries.

As a result, it is obvious that economic growth is important for countries but it is not good in terms of environmental impact, and that energy regulations and sustainable industrial transformation strategies are needed for this process to yield positive environmental results. To achieve sustainable development goals,

every country should prioritize carbon neutrality targets in the industrial sector, increase energy efficiency investments, and encourage the use of renewable energy.

Country-specific results reveal several important patterns that can be summarised as follows:

(i) In high-income OECD countries such as France, the Netherlands, Sweden and Austria, economic growth tends to reduce CO_2 emissions in the long term. This shows that economic growth in these countries is progressing in line with environmental sustainability policies. This situation demonstrates that technological innovations, energy efficiency measures and green transition investments play an effective role in reducing emissions. This situation supports the Environmental Kuznets Curve hypothesis and demonstrates that technological innovations, energy efficiency measures and green transition investments play an effective role in reducing emissions.

(ii) In countries such as the United States, Canada, and Mexico, where energy consumption is largely based on fossil fuels, increases in energy use continue to have a strong positive impact on CO_2 emissions. The energy consumption (EC) variable has a strong and significant effect on increasing CO_2 emissions in many countries. This clearly demonstrates the carbon-intensive nature of energy use and shows that, despite high income levels, the energy-emissions link remains a significant environmental problem.

(iii) The impact of the industrial sector varies from country to country. The fact that the industrial sector share (IND) variable has negative effects in some countries (France, USA, Poland and the Netherlands) and positive effects in others (Turkey, Germany, Italy, Spain, etc.) is related to structural differences in the industrialisation process. While industrial expansion increases emissions in some economies, the adoption of cleaner production technologies in others mitigates this effect, highlighting the importance of sector-specific green transition policies.

Future studies could further explore the analysis by incorporating factors such as population growth, urbanization rate, foreign trade volume, and technical progress in addition to the variables presented in this article. Furthermore, including other country groups would allow for observation and comparison of these interactions across different country groups.

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