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# Testing the environmental Kuznets Curve hypothesis at the sector level: Evidence from PNARDL for OECD countries

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Since the contribution of economic sectors to GDP is heterogeneous, they also contribute differently to CO<sub>2</sub> emissions and environmental degradation. In this regard, it is crucial to examine the Environmental Kuznets Curve (EKC) hypothesis at the sectoral level. Nevertheless, despite the extensive research conducted on the Environmental Kuznets Curve (EKC) hypothesis, significant gaps remain in the existing literature, particularly at the sectoral level. This study makes a novel contribution to the existing literature on the environmental EKC hypothesis by examining its validity across four distinct sectors: agriculture, industry, manufacturing, and services. Additionally, it makes a second contribution to the literature by examining the effect of energy consumption on CO<sub>2</sub> asymmetrically, employing a novel panel non-linear ARDL (PNARDL) method. The study employs annual data from 38 OECD countries, spanning the period from 1990 to 2022. The findings demonstrate that the EKC hypothesis is valid for sectors other than the industrial sector and for the economy as a whole. The turning point of the Kuznets Curve for the total economy is estimated as \$29250 GDP *per capita*. The PNARDL model's error correction term (ect) is negative and significant. However, the magnitude of the term suggests that the system will return to long-term equilibrium after approximately 2.87 years following any shock. Asymmetric effects are valid for four sectors. Moreover, the empirical results clearly show that energy consumption has asymmetric effects on emissions in both the long and short run. Positive and negative shocks in energy consumption increase CO<sub>2</sub> emissions in OECD economies in the long run. It has been determined that agriculture is the sector that causes the most environmental degradation by increasing CO<sub>2</sub> emissions. This situation highlights the limited availability of productive capital equipment and renewable sources in the agricultural sector, even in OECD countries. As a result, the findings show that there is a different relationship between each sector's GDP and CO<sub>2</sub> emissions. It is important for policymakers to formulate sector-specific policies to reduce CO<sub>2</sub> emissions while fostering GDP growth.

## KEYWORDS

energy consumption, environmental degradation, EKC hypothesis, panel NARDL, OECD countries

## 1 Introduction

The transformation of production processes that commenced with the Industrial Revolution has led to a rapid increase in energy consumption. The surge in energy production and consumption, particularly post-1980, has exerted significant pressure on the ecological balance (Song et al., 2021). Consequently, societies have prioritized addressing various environmental issues, such as climate change and global warming (Mujtaba et al., 2020; Ozcan et al., 2019). Primary energy sources are recognized as major contributors to global warming and environmental pollution (Gyamfi et al., 2021; Usman et al., 2022; Zhang et al., 2023). Global energy-related CO<sub>2</sub> emissions grew by 0.9% or 321 Mt in 2022, reaching a new high of over 36.8 Gt (IEA, 2022). If no action is taken to address this situation, the likelihood of global temperatures rising by 4°C is 75%, and the likelihood of a rise by 8°C is 21% (Waldhoff and Fawcett, 2011). Therefore, high primary energy use causes environmental pollution and environmental degradation.

Energy use is directly linked to economic growth. Therefore, energy consumption is one of the most important responsible for environmental quality (Sinha et al., 2017). The pioneer of studies examining environmental pollution and economic growth are the studies of Grossman and Krueger (1991). They concluded that at lower national income levels, carbon dioxide emissions increase with GDP *per capita*, but at higher income levels, environmental pollution decreases. Other studies (Panayotou, 1993; Cole et al., 1997) also confirmed the inverted “U” curve between economic income and environmental degradation. In this context, based on the Kuznets Curve proposed by Kuznets (1955), the relationship between environment and income was accepted as the Environmental Kuznets Curve (EKC) in the literature. According to EKC, there is an inverted U-shaped correlation between environmental quality and income. Based on this, the relationship between carbon emissions and income under the EKC hypothesis has been the subject of many studies in the last 30 years (Selden and Song, 1994; Cole et al., 1997; Lean and Smyth, 2010; Van Hoa and Limskul, 2013; Kais and Sami, 2016; Balsalobre-Lorente et al., 2018; Nabavi-Pelesaraei et al., 2018; Kaab et al., 2019; Nabavi-Pelesaraei et al., 2019; Zafar et al., 2019; Cheikh et al., 2021; Wang et al., 2023; Sanli et al., 2023). These studies generally provide evidence of an inverted U-shaped relationship. Additionally, numerous studies in the literature provide evidence supporting the validity of the EKC hypothesis in different samples and with different environmental pollution indicators (Yilanci et al., 2022).

Although the relationship between environmental pollution and economic growth has been extensively studied by academics, it remains one of the most challenging issues for the global community. The validity of the EKC hypothesis has generally been examined in the literature for the entire economy. However, recent literature indicates that the economic structure plays a crucial role in assessing the validity of the EKC hypothesis. Neglecting this aspect may lead to misleading conclusions regarding the validity of the EKC hypothesis (Taşdemir, 2022). The relationship between carbon dioxide emissions and income may differ across economic sectors. Each sector's energy requirements within an economy can differ based on the availability of energy resources, technological development, economies of scale, and government-implemented policies. For this reason, the fact that different sectors follow

different paths in the production process may cause the relationship between carbon dioxide emissions and income to differ (Htike et al., 2021).

Limited attention has been paid in the literature to the validity of the EKC hypothesis on a sectoral basis. While the validity of the EKC hypothesis was examined from a sectoral perspective in the literature, the asymmetric effects of the variables were ignored. Therefore, this study examines the validity of the EKC hypothesis at the sectoral level for OECD countries using non-linear analysis techniques. OECD countries have a significant share in the world economy. The world's total GDP in 2022 was 89.9 trillion dollars. OECD countries account for approximately 60% of this GDP value (\$53.7 trillion) (WDI, 2023). Based on our literature review, there is only one article (Fujii and Managi, 2013) in the literature that investigates the EKC by sectors for 23 OECD countries, the first important gap in the literature is not to have research which considers all 38 member countries of OECD. The second gap is that the most recent study for a group of countries that are important economic powers such as OECD countries used 2005 data and no study has been conducted with current data. In our paper we use data from 38 OECD countries and the period is 1990–2022. In addition, our most important contribution to the relevant literature is to investigate the validity of the EKC hypothesis by taking into account the asymmetric effects with nonlinear analysis techniques.

The aim of this study is to examine the validity of the EKC hypothesis at the sectoral level for OECD countries. While numerous studies in the literature have explored the EKC hypothesis, there are still gaps, particularly at the sectoral level. The most important contribution of this study to the literature is the examination of the EKC hypothesis at the sectoral level with non-linear analysis techniques.

Compared to the number of papers investigating the EKC hypothesis in the context of the general economy, sector-based EKC papers are fewer and more recent. It can be seen from Table 1; the studies have been constricted to a limited number of sectors generally and country groups. In our literature review, we found only one article on OECD countries and none of the studies are on the OECD covering the last two decades. In our literature review, we found only one article on OECD countries and no study on the OECD covering the last 2 decades. In terms of the sector analyzed, while some articles focus on one sector, there are studies focusing on a few selected sectors or many more sectors. When the literature is examined, it is seen that there is no article using non-linear modeling and this is a gap in the literature. This study focuses on OECD countries, which have rarely been addressed in papers testing the EKC hypothesis at the sectoral level, and also models the relationship with a non-linear method that has not been used before in studies conducted in this context. We present a unique methodology to test the EKC hypothesis in OECD by showing their asymmetric movements. In this study, we not only show the asymmetric relationship, but also the long-run relationship and causality between the variables, but we emphasize the asymmetric relationship because it has not been addressed before.

In this context, the validity of the EKC hypothesis was investigated for the entire economy as well as for the agriculture, industry, manufacturing, and services sectors. In addition to the fact that the study is at a sectoral level, bringing together 38 OECD

TABLE 1 A brief literature.

Author	Period	Country/Region	Sector	Methodology	Conclusion
Hamit-Haggar, (2012)	1990–2007	Canada	21 industrial sectors	Panel data regression	Support EKC
Ben Abdallah et al. (2013)	1980–2010	Tunisia	Road transport sector	VECM	No evidence of EKC
Fujii and Managi, (2013)	1970–2005	OECD countries	9 industries	Panel data regression	Support EKC for some sectors
Ren et al. (2014)	2000–2010	China	18 industries	Panel data regression	Support EKC
Xu and Lin, (2015)	2000–2012	China	Transport sector	Nonparametric additive regression	Support EKC
Congregado et al. (2016)	1973–2015	United States	Four sectors (industrial, electricity production, transportation, residential and commercial) and total	Dynamic Ordinary Least Squares, Arai-Kurozumi-Kejriwal cointegration tests with structural breaks	Support EKC excluding the industrial sector
Xu and Lin, (2016)	2000–2013	30 Chinese provinces	Manufacturing industry	Nonparametric additive regression	Support EKC
Fujii and Managi, (2016)	1995–2009	39 countries	16 industries and whole country	Panel data regression	Support EKC for some industries
Moutinho et al. (2017)	1975–2012	Portugal and Spain	13 sectors	Panel Corrected Standard Errors	Not supported EKC under the quadratic specification
Pablo-Romero et al. (2017)	1995–2009	27 EU countries	Transport sector	Feasible Generalized Least Squares	Turning point of the EKC is not reached, N-shaped curve if prices are included
Xu and Lin, (2017)	2000–2013	30 Chinese provinces	Iron and steel industry	Nonparametric additive regression	Inverted U-shaped, U-shaped
Wang et al. (2017)	2000–2013	30 Chinese provinces	Three sectors (mining, manufacturing, electricity, and heat production)	Parametric model Semi-parametric panel regression model	Inverted U-shaped curve for electricity and heat production
Ahmad et al. (2019)	2000–2016	30 Chinese provinces	Construction sector	AMG and DCCEMG estimator	Support EKC
Ma et al. (2019)	2000–2015	China	Chinese commercial buildings	Decomposition and decoupling analysis	Inverted U-shaped
Zhang et al. (2019)	1960–2014	121 countries	Manufacturing and construction industries	Top-down approach	Support EKC in 95 countries
Erdogan et al. (2020)	1995–2014	10 air passenger-carrier countries	Transport sector	Mean-Group, FMOLS estimation	Support EKC
Raza et al. (2020)	1990–2015	N-11 and BRICS	Residential sector	Panel Cointegration, Panel Causality, FMOLS	Support EKC
Htike et al. (2021)	1990–2015	86 developing countries	Seven sectors (electricity and heat production, manufacturing and construction, residential, transport, commercial and public services, agriculture, forestry, and fishing, other energy industry own use)	Panel ARDL model (Panel Mean Group -ARDL)	Electricity and heat production, commercial and public services, and other energy industry own use follow the EKC patterns
Pata et al. (2023)	1995–2019	13 EU countries	Transportation sectors (railway, road, air, maritime)	AMG estimation	Inverted U-shaped, U-shaped
Hashmi et al. (2024)	2000–2020	US	Five sectors (Transport, industrial, electric Power, residential sector, commercial)	SOR unit root test Fourier ARDL model	Existence of the EKC hypothesis in all sectors

DCCEMG: dynamic common correlated effects mean group. AMG: augmented means group. FMOLS: fully modified ordinary least squares.

countries at the same time constitutes an important contribution of this study. On the other hand, the validity of the EKC hypothesis may be affected by the chosen econometric models and methods (Dinda, 2004; Stern, 2004; Pablo-Romero et al., 2017). For this

reason, the study also examined the asymmetric relationships between energy consumption and carbon dioxide emissions within the framework of the model established. Unlike other studies in the literature, the Nonlinear Panel Autoregressive

Distributed Lag (PNARDL) method was employed in this study, marking another noteworthy contribution to the literature.

The remainder of this study is organized as follows. The relevant literature review is presented in Section 2. Section 3 describes the econometric methodology used in the study. Section 4 provides information about the dataset used in the study. In Section 5, the study's findings are presented. Section 6 concludes the article by discussing the findings.

## 2 Literature review

There literature about environmental Kuznets curve (EKC) hypothesis is very wide. The hypothesis of EKC claims that the relationship between economic growth and environmental pollution shows an inverted U-shaped relationship (Grossman and Krueger, 1991). Grossman and Krueger (1991) is a pioneering study of EKC hypothesis, many research followed this study and find different results such as U-shaped (Aslam et al., 2021; Brown et al., 2020; Isik et al., 2020; Pata, 2021), N-shaped (Bekun et al., 2021; Friedl and Getzner, 2003; Lorente and Álvarez-Herranz, 2016; Vincent, 1997) and inverted N-shaped (Esmailpour Moghadam and Dehbashi, 2018; Shao et al., 2011). Naveed et al. (2022) reveal the high number of studies that have been carried out on this subject by using 1,654 articles (1992–2022 period) on EKC from Scopus-Indexed journals in their literature review and content analysis. The authors state that thousands of academic papers aimed to test the likelihood of such an inverted U-shaped relationship since the 1990s. Their literature review shows that based on the total citations count of the papers the main papers about EKC are Arouri et al. (2012); Dinda (2004); Jalil and Feridun (2011); Kasman and Duman (2015); Sarkodie and Strezov (2019); Selden and Song (1994); Soytaş et al. (2007); Stern (2004); Torras and Boyce (1998). The last information we use from the paper is that 62% of the studies reported the shape of EKC, 14% of the studies reported the U-shape, and the rest of the papers of the studies were reported other shapes.

In the literature the studies investigated EKC for the country, group of countries, region, or sector. In this paper we investigate the EKC in sector level and we found several studies in sector level. The papers which investigate sectors are Ben Abdallah et al. (2013); Hamit-Haggag (2012); Ma et al. (2019); Ren et al. (2014); Xu and Lin (2015, 2016) for country level and Ahmad et al. (2019); Fujii and Managi (2013, 2016); Pata (2018); Xu and Lin (2016, 2017) for group of country level. We summarized these papers in Table 1.

Pata et al. (2023) select for the four transport modes in the 13 EU countries which are Belgium, Denmark, Finland, France, Germany, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden and United Kingdom; and findings show that the EKC is valid for at least one transport mode in 10 of the 13 EU countries. Ahmad et al. (2019) uses gross regional product, urban population, added value of construction, energy consumption and population in their study then estimate several models by using AMG and DCCEMG models. The results show that long-run equilibrium relationship is confirmed among energy consumption, gross regional product and growth in the construction sector continues to be one of the key drivers of energy use and CO<sub>2</sub> emissions.

Our literature review reveals that the only study on OECD countries is Fujii and Managi (2013). This study analyses sectors such as chemicals, construction, food and tobacco, manufacturing, machinery and construction, non-metallic minerals, paper, pulp and printing, steel and metal, transport equipment, wood and wood products between 1970 and 2005. 23 countries are used in the research. The results show that overall CO<sub>2</sub> emissions show an N-shaped relationship and the EKC hypothesis for sector-level CO<sub>2</sub> emissions was supported in wood and wood products, paper, pulp, and printing, and construction industries. Fujii and Managi, (2016) analyze eight environmental air pollutants carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), nitrogen oxide (NO<sub>x</sub>), sulfur oxide (SO<sub>x</sub>), carbon monoxide (CO), non-methane volatile organic compound (NMVOC), and ammonia (NH<sub>3</sub>), for whole country, 16 industries (industrial sector, mining and quarrying, food, beverages, and tobacco, textiles and textile products, leather, leather, and footwear, wood and products of wood and cork, pulp, paper, paper, printing, and publishing, coke, refined petroleum, and nuclear fuel, chemicals and chemical products, rubber and plastics, other non-metallic mineral, basic metals and fabricated metal, machinery, Nec, electrical and optical equipment, transport equipment, electricity, gas, and water supply, and construction) and find that CO<sub>2</sub>, N<sub>2</sub>O, and NMVOC emissions are observed to have EKC relationships on both the country level and the total industry level.

## 3 Econometric approach

The aim of this study is to examine the validity of the environmental EKC hypothesis for four different sectors (Agriculture, Industry, Manufacturing and Services) and to analyze the impact of energy consumption on CO<sub>2</sub> asymmetrically. In accordance with this purpose, various steps were applied for econometric analysis.

Firstly, autocorrelation is analyzed using Wooldridge test for autocorrelation, heteroskedasticity is analyzed using Modified Wald test for groupwise heteroskedasticity and multicollinearity is analyzed using CD test for cross-section dependency.

Secondly, in line with the results obtained from the analysis, stationarity is tested with Pesaran (2007) CADF panel unit root test. Cointegration in the study was determined by Westerlund (2005) and Pedroni (1999, 2004) panel cointegration tests. The existence and direction of causal relationships in the panel are investigated with the JKS non-causality test (Juodis et al., 2021). Panel nonlinear ARDL was applied to examine the long-run parameters (Shin et al., 2014).

The empirical model explaining the EKC hypothesis for the OECD can be explained as follows in line with the purpose of the study and based on previous studies:

$$CO_{2it} = f(GDP_{it}, GDP_{it}^2, EN_{it}, K_{it}, POP_{it})$$

Where  $f$  is a functional representation, CO<sub>2</sub>, GDP, GDP<sup>2</sup>, EN, K, POP;  $t$  denote carbon dioxide emissions, gross domestic product, GDP squared, energy consumption, capital and population in the OECD at time  $t$ , respectively.

Based on the functional representation, we constructed the model in Equation 1 to explain CO2 emissions in OECD countries.

$$CO2_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 EN_{it} + \beta_4 K_{it} + \beta_5 POP_{it} + \mu_{it} \quad (1)$$

where  $\beta_0$  is the country fixed effect,  $CO2_{it}$  is the logarithm of carbon dioxide emissions,  $GDP_{it}$  is the logarithm of real gross domestic product,  $GDP_{it}^2$  is the logarithm of real gross domestic product squared,  $EN_{it}$  is the logarithm of primary energy supply,  $K_{it}$  is logarithm of capital stock,  $POP_{it}$  is the logarithm of population and  $\mu_{it}$  is an independently and normally distributed error term.

The main objective of this study is to analyze the effects of sectoral GDPs and total GDP on CO2. However, it is important to analyze the positive and negative effects of energy consumption on CO2 with the help of a single model. In addition, an approach that can be used in non-stationary panels will be appropriate if the data of the variables to be used in the analysis contain unit roots. Panel ARDL method can be used in panels with non-stationary series. The linear panel ARDL approach was developed by Pesaran et al. (1996; 2001). According to the variables included in the analysis, we can represent the linear panel ARDL equation as in Equation 2.

$$\begin{aligned} \Delta CO2_{it} = & \alpha_i + \gamma_{1i} CO2_{i,t-1} + \gamma_{2i} GDP_{i,t-1} + \gamma_{3i} GDP_{i,t-1}^2 + \gamma_{4i} POP_{i,t-1} \\ & + \gamma_{5i} EN_{i,t-1} + \sum_{j=1}^{p_1} \delta_{1ij} \Delta CO2_{i,t-j} + \sum_{j=1}^{p_2} \delta_{2ij} \Delta GDP_{i,t-j} \\ & + \sum_{j=1}^{p_3} \delta_{3ij} \Delta GDP_{i,t-j}^2 + \sum_{j=1}^{p_4} \delta_{4ij} \Delta POP_{i,t-j} \\ & + \sum_{j=1}^{p_5} \delta_{5ij} \Delta EN_{i,t-j} + \varepsilon_{it} \end{aligned} \quad (2)$$

Where  $\Delta$  denotes the first difference,  $\alpha_i$  is the constant term,  $\delta_{sij}$  ( $s = 1, 2, 3, 4, 5, 6$ ) is the short-run coefficients,  $\gamma_{ki}$  ( $k = 1, 2, 3, 4, 5, 6$ ) is the long-run coefficients,  $\varepsilon_{it}$  is the error term. The optimal lag lengths of the first differenced variables ( $p_1, p_2, p_3, p_4, p_5, p_6$ ) are determined according to the information criterion. Equation 3 represents Equation 2 with the error correction term added.

$$\begin{aligned} \Delta CO2_{it} = & \varphi_i + \sum_{j=1}^{p_1} \delta_{1ij} \Delta CO2_{i,t-j} + \sum_{j=1}^{p_2} \delta_{2ij} \Delta GDP_{i,t-j} \\ & + \sum_{j=1}^{p_3} \delta_{3ij} \Delta GDP_{i,t-j}^2 + \sum_{j=1}^{p_4} \delta_{4ij} \Delta POP_{i,t-j} \\ & + \sum_{j=1}^{p_5} \delta_{5ij} \Delta EN_{i,t-j} + \lambda_i ect_{i,t-1} + \varepsilon_{it} \end{aligned} \quad (3)$$

Where the linear error correction term is denoted by  $ect_{i,t-1}$ . The parameter  $\lambda_i$  is equivalent to  $\gamma_{1i}$  and represents the speed of error correction in the adjustment of the model to equilibrium for each unit.

Moreover, the non-linear panel ARDL method of Shin et al. (2014) based on the dynamic representation of heterogeneous panel data in the presence of asymmetry is also an appropriate approach to capture the short-run dynamics of variables and their adjustment to long-run equilibrium. However, the nonlinear panel ARDL approach is an asymmetric extension of the linear panel ARDL approach, and the nonlinear model is to detect short and long-run asymmetric movements with the help of an asymmetric error correction model.

The nonlinear panel ARDL approach allows for asymmetric responses of CO2 emissions to primary energy consumption and

decomposes the exogenously fluctuating variable into two partial aggregates. The idea is that positive and negative shocks to primary energy consumption are expected to have different effects on CO2 emissions.

$$\begin{aligned} EN_{i,t}^+ &= \sum_{j=1}^t \Delta EN_{i,j}^+ = \sum_{j=1}^t \max(\Delta EN_{i,j}^+, 0) \\ EN_{i,t}^- &= \sum_{j=1}^t \Delta EN_{i,j}^- = \sum_{j=1}^t \min(\Delta EN_{i,j}^-, 0) \end{aligned} \quad (4)$$

The nonlinear panel ARDL model constructed by adding short-run and long-run asymmetric relationships to the linear panel ARDL model in Equation 3 is shown in Equation 5.

$$\begin{aligned} \Delta CO2_{it} = & \eta_i + \gamma_{1i} CO2_{i,t-1} + \gamma_{2i} GDP_{i,t-1} + \gamma_{3i} GDP_{i,t-1}^2 + \gamma_{4i} POP_{i,t-1} \\ & + \gamma_{5i}^+ EN_{i,t-1}^+ + \gamma_{5i}^- EN_{i,t-1}^- + \sum_{j=1}^{p_1} \delta_{1ij} \Delta CO2_{i,t-j} \\ & + \sum_{j=1}^{p_2} \delta_{2ij} \Delta GDP_{i,t-j} + \sum_{j=1}^{p_3} \delta_{3ij} \Delta GDP_{i,t-j}^2 \\ & + \sum_{j=1}^{p_4} \delta_{4ij} \Delta POP_{i,t-j} + \sum_{j=1}^{p_5} (\delta_{5ij}^+ \Delta EN_{i,t-j}^+ + \delta_{5ij}^- \Delta EN_{i,t-j}^-) \\ & + \varepsilon_{it} \end{aligned} \quad (5)$$

The estimates from the coefficients  $\delta_{5ij}^+$  and  $\delta_{5ij}^-$  show the short-term asymmetric response of CO2 to positive and negative shocks in primary energy consumption, while the long-term asymmetric response is estimated from the coefficients  $\gamma_{5i}^+$  and  $\gamma_{5i}^-$ . The asymmetric error correction term is shown in Equation 6.

$$\begin{aligned} \Delta CO2_{it} = & \tau_i + \sum_{j=1}^{p_1} \delta_{1ij} \Delta CO2_{i,t-j} + \sum_{j=1}^{p_2} \delta_{2ij} \Delta GDP_{i,t-j} \\ & + \sum_{j=1}^{p_3} \delta_{3ij} \Delta GDP_{i,t-j}^2 + \sum_{j=1}^{p_4} \delta_{4ij} \Delta DEN_{i,t-j} \\ & + \sum_{j=1}^{p_5} (\delta_{5ij}^+ \Delta EN_{i,t-j}^+ + \delta_{5ij}^- \Delta EN_{i,t-j}^-) + \theta_i ect'_{i,t-1} \varepsilon_{it} \end{aligned} \quad (6)$$

The asymmetric error correction term is denoted by  $ect'_{i,t}$ , where  $\theta_i$  is the rate at which the system returns to long-run equilibrium after a shock.

## 4 Data

The raw data used in the study were obtained from the World Bank's World Development Indicators (WDI) and International Energy Agency (IEA) databases covering 38 OECD countries for the period 1990–2022 and processed by the authors. Information on the variables in the data set is presented in Table 2.

Capital stock data are computed from the investment series using the perpetual inventory method (PIM) following Nehru and Dhreshwar (1993) and Harberger (1978). In order to transform the data set from an unbalanced panel to a balanced panel, a small number of missing observations were estimated by the linear method.

Moreover, natural logarithm is used for all variables to obtain elasticities in a straightforward form and to mitigate heteroscedasticity. In order to minimize the scale effect of economies, all variables have been converted into *per capita* units.

TABLE 2 Variable descriptions.

Variables	Abbreviation	Definition	Unit	Source
CO2	lny	Carbon dioxide emission	Metric tons <i>per capita</i>	World Bank database
EN	lnx1	Primary energy consumption	kWh <i>per capita</i>	International Energy Agency database
K	lnx2	Capital Stock	Constant 2015 US\$ <i>per capita</i>	Authors' own calculation from World Bank database
POP	lnx3	Population, Total	Number of people	Authors' own calculation from World Bank database
GDP	lnx4	Real Gross Domestic Product	Constant 2015 US\$ <i>per capita</i>	Authors' own calculation from World Bank database
GDP_A	lnx5	Agriculture, forestry, and fishing, value added	Constant 2015 US\$ <i>per capita</i>	Authors' own calculation from World Bank database
GDP_I	lnx6	Industry (including construction), value added	Constant 2015 US\$ <i>per capita</i>	Authors' own calculation from World Bank database
GDP_M	lnx7	Manufacturing, value added	Constant 2015 US\$ <i>per capita</i>	Authors' own calculation from World Bank database
GDP_S	lnx8	Services, value added	Constant 2015 US\$ <i>per capita</i>	Authors' own calculation from World Bank database

TABLE 3 Descriptive statistics of variables.

Variable	N	Mean	sd	Variance	cv	se (mean)	Skewness	Kurtosis	min	max	Jarque-Bera
lny	1,254	1.943	0.584	0.342	0.301	0.017	-0.683	3.959	-0.094	3.413	145.542
ln (x1) <sup>-</sup>	1,254	4.854	5.317	28.266	1.095	0.150	0.191	1.056	0.000	12.117	3,929.281
ln (x1) <sup>+</sup>	1,254	5.765	5.303	28.123	0.920	0.150	-0.153	1.053	0.000	12.146	2,840.740
lnx2	1,254	11.183	0.875	0.766	0.078	0.025	-0.668	2.543	8.987	12.782	104.169
lnx3	1,254	16.325	1.510	2.281	0.093	0.043	-0.207	2.832	12.448	19.625	10.43
lnx4	1,254	6.237	0.563	0.317	0.090	0.016	0.754	4.919	4.509	8.268	311.216
lnx5	1,254	8.704	0.730	0.533	0.084	0.021	-0.336	2.544	7.029	10.723	34.497
lnx6	1,254	8.113	0.761	0.579	0.094	0.021	-0.390	2.793	6.265	10.666	33.968
lnx7	1,254	9.630	0.834	0.695	0.087	0.024	-0.385	2.328	7.494	11.505	54.580
lnx8	1,254	10.100	0.770	0.593	0.076	0.022	-0.428	2.315	8.214	11.630	62.712

## 5 Empirical findings

We initiate the analysis of the series compiled from the data of OECD countries by presenting descriptive statistics. Table 3 presents the descriptive statistics of the variables in the models.

ln (x1)<sup>-</sup> and ln (x1)<sup>+</sup> represent the negative and positive components of the energy consumption data obtained through Equation 4, respectively. Firstly, the high variance and standard deviation statistics of energy consumption series (lnx1<sup>-</sup> and lnx1<sup>+</sup>) in the table are remarkable. This indicates the existence of volatility and heterogeneity in terms of energy consumption in OECD economies. A very similar situation is also valid for the population (lnx3).

Table 4 shows the pairwise correlation matrix of the variables. As expected, CO2 emissions are positively correlated with the GDP *per capita* of the sectors. While the energy consumption increase

series is negatively correlated with CO2, the energy consumption decrease series is positively correlated with CO2. In addition, CO2 emissions are positively correlated with the level of capital stock. However, there is no significant correlation between population and CO2.

Cross-sectional dependence in the series is examined using the parametric test procedure proposed by Pesaran (2004) under the null hypothesis of cross-sectional independence using both variables and residuals (see Table 5). The results show that, at the 1% significance level, the null hypothesis of cross-sectional independence is rejected for all series in the dataset.

However, the findings regarding heteroskedasticity and autocorrelation in identifying residuals diagnostic are given in Table 6. The Wooldridge test for autocorrelation in the panel data shows that the null hypothesis of first-order autocorrelation

TABLE 4 Pairwise correlations.

Variables	lny	ln (x1) <sup>-</sup>	ln (x1) <sup>+</sup>	lnx2	lnx3	lnx4	lnx5	lnx6	lnx7	lnx8
lny	1.000									
ln (x1) <sup>-</sup>	0.139*** (0.000)	1.000								
ln (x1) <sup>+</sup>	-0.050* (0.076)	-0.993*** (0.000)	1.000							
lnx2	0.605*** (0.000)	0.162*** (0.000)	-0.076*** (0.007)	1.000						
lnx3	-0.020 (0.484)	-0.006 (0.833)	-0.016 (0.561)	-0.042 (0.138)	1.000					
lnx4	0.112*** (0.000)	-0.012 (0.662)	0.059** (0.035)	0.382*** (0.000)	-0.230*** (0.000)	1.000				
lnx5	0.566*** (0.000)	0.145*** (0.000)	-0.062** (0.029)	0.924*** (0.000)	-0.048* (0.092)	0.414*** (0.000)	1.000			
lnx6	0.520*** (0.000)	0.142*** (0.000)	-0.069** (0.014)	0.900*** (0.000)	-0.014 (0.628)	0.355*** (0.000)	0.941*** (0.000)	1.000		
lnx7	0.600*** (0.000)	0.167*** (0.000)	-0.082*** (0.004)	0.951*** (0.000)	-0.096*** (0.001)	0.388*** (0.000)	0.930*** (0.000)	0.888*** (0.000)	1.000	
lnx8	0.594*** (0.000)	0.164*** (0.000)	-0.078*** (0.006)	0.957*** (0.000)	-0.111*** (0.000)	0.409*** (0.000)	0.955*** (0.000)	0.906*** (0.000)	0.993*** (0.000)	1.000

Probability values in parentheses. \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

is rejected with 1% statistical significance. Furthermore, the modified Wald statistic for testing groupwise heteroskedasticity indicates that the null hypothesis is rejected.

Table 7 shows the level and first difference statistics of Pesaran (2007) CADF panel unit root test in the presence of cross-sectional dependence in the variables. The optimal lag length for the unit root test was determined using AIC. The findings of the CADF test with the constant and trend option show that all variables are I (1). Variables that are non-stationary in levels are stationary in their first differences.

Panel cointegration tests proposed by Westerlund (2005) and Pedroni (1999, 2004) have also been applied to test for the existence of a structural long-run relationship between variables. These tests are robust to cross-sectional dependence. The procedure of Levin et al. (2002) was followed for cross-sectional robustness of the statistics. Table 8 shows the computed values of cointegration tests. The statistics indicate that the null hypothesis of no cointegration should be rejected. In this case, cointegration relationship between the variables is valid and there are structural relationships between them in the long run.

The statistics presented in Table 9 show that the null hypothesis of the Juodis, Karavias, and Sarafidis (2021) JKS test should be rejected. Therefore, the explanatory variables in the models are the

granger causes of carbon emissions. The JKS (2021) test provided evidence that the past values of the increase and decrease series of energy consumption, capital stock, population and GDP *per capita* are useful in forecasting CO<sub>2</sub> in addition to the past values of CO<sub>2</sub> alone.

The coefficient of the ECT is significant and negative, confirming the cointegration relationship between the variables. The ECT results of the models show that the system returns to long-run equilibrium in the range of 2.67 years (33 months) - 3.22 years (39 months) after a shock. However, there is strong evidence for the validity of the EKC hypothesis in other sectors excluding industry (see Table 10). Asymmetric effects of energy consumption are valid in the short and long run. The findings indicates that both an increase and decrease in *per capita* energy consumption lead to a rise in carbon emissions across all sectors and the economy as a whole, resulting in a decline in environmental quality (see Tables 10, 11). The impact of capital stock (lnk) and population (lnpop) on CO<sub>2</sub> emissions is negative. The decrease in CO<sub>2</sub> emissions due to an increase in capital stock is attributed to the efficient production structure of capital equipment. Similarly, the effect of population is believed to be linked to economies of scale. As the size of the country increases, cleaner and more efficient energy resources and capital-intensive production methods are employed.

TABLE 5 Variables cross sectional dependency test results.

Variables	CD-test	$p$ -value	Mean $\rho$	Mean abs( $\rho$ )
lny	48.847	0.000	0.320	0.560
ln (x1) <sup>-</sup>	18.531	0.000	0.120	0.190
ln (x1) <sup>+</sup>	18.189	0.000	0.120	0.190
lnx2	129.907	0.000	0.850	0.860
lnx3	67.655	0.000	0.440	0.850
lnx4	20.235	0.000	0.130	0.450
lnx5	72.490	0.000	0.480	0.550
lnx6	70.619	0.000	0.460	0.620
lnx7	141.424	0.000	0.930	0.930
lnx8	137.922	0.000	0.910	0.910
(lnx4) <sup>2</sup>	20.261	0.000	0.130	0.450
(lnx5) <sup>2</sup>	72.362	0.000	0.480	0.550
(lnx6) <sup>2</sup>	70.335	0.000	0.460	0.620
(lnx7) <sup>2</sup>	141.171	0.000	0.930	0.930
(lnx8) <sup>2</sup>	137.735	0.000	0.900	0.900

CD, test H0: Cross-section independence, CD  $\sim$  N (0,1).  $p$ -values close to zero indicate data are correlated across panel groups.  $\rho$ : Correlation coefficient.

TABLE 6 Residual diagnostic.

Test type	Model I (Agricul.)	Model II (Industry)	Model III (Manufac.)	Model IV (Service)	Model V (Total Econ.)
Wooldridge test for autocorrelation	135.914 [0.000]	109.476 [0.000]	119.625 [0.000]	122.985 [0.000]	123.913 [0.000]
Modified Wald test for groupwise heteroskedasticity	4310.43 [0.000]	3946.23 [0.000]	3939.25 [0.000]	2277.12 [0.000]	2105.64 [0.000]
CD test for cross-section dependency	20.012 [0.000]	19.345 [0.000]	20.122 [0.000]	20.837 [0.000]	22.801 [0.000]

Wooldridge test H0: No first order autocorrelation. Modified Wald test H0: Homoskedasticity. CD, test H0: Cross-section independence. Probability values in brackets.

In the service sector, the capital stock has no effect on CO<sub>2</sub> emissions, while increases in the capital stock of other sectors lead to significant reductions in environmental degradation.

The fact that energy consumption increases environmental degradation in all sectors and the entire economy is still due to the intensity of primary energy use in the countries under consideration. Although the use of renewable energy has increased in OECD countries in recent years, this is still not at the desired level. In addition, the fact that the EKC hypothesis is not valid in the industry sector may be due to the intensive use of primary energy in the industry sector. Therefore, governments should reconsider their energy policies, especially in the industry sector, and should definitely increase renewable energy investments. It is seen that the coefficient value of the capital stock in the services sector is meaningless. This may be due to the fact that the capital stock used in the service sector is predominantly fixed assets. When all these are evaluated together, our findings provide important

contributions to the literature. The first of these contributions is the demonstration that the asymmetric effects of energy consumption in all sectors and the economy in general have the same effect. In addition, in addition to the fact that the EKC hypothesis is not valid in the industrial sector of OECD countries, the fact that the validity of the EKC hypothesis in agriculture, manufacturing and service sectors is put forward also makes significant contributions to the literature.

Since 2022 is the last year of the data set, the estimated turning point graph for 2022 is presented in [Graph 1](#). Of the 38 OECD countries, 16 are on the positively sloping part of the Kuznets curve (to the left of the turning point), according to the GDP *per capita* data corresponding to the estimated turning point obtained from the regression. The *per capita* income of these countries is below USD 29250, and environmental degradation continues to increase (see [Graph 1](#)). The fact that the EKC turning point shows significant differences among sectors is related to the share of the relevant



TABLE 7 CADF unit root test results.

Variable	lny	ln (x1) <sup>-</sup>	ln (x1) <sup>+</sup>	lnx2	lnx3	lnx4	lnx5	lnx6	lnx7	lnx8	(lnx4) <sup>2</sup>	(lnx5) <sup>2</sup>	(lnx6) <sup>2</sup>	(lnx7) <sup>2</sup>	(lnx8) <sup>2</sup>
<b>Panel A: Level</b>															
t-bar	-2.019	-2.348	-2.337	-1.917	-1.493	-1.844	-1.553	-1.670	-2.084	-1.944	-1.831	-1.507	-1.610	-2.008	-1.901
Z [t-bar]	2.252	-0.059	0.023	2.966	5.935	3.476	5.513	4.695	1.792	2.771	3.562	5.835	5.114	2.326	3.074
p-value	0.988	0.476	0.509	0.998	1.000	1.000	1.000	1.000	0.963	0.997	1.000	1.000	1.000	0.992	0.999
<b>Panel B: First Differences</b>															
t-bar	-2.894	-2.983	-2.980	-2.708	-2.711	-3.233	-2.691	-2.785	-2.709	-2.730	-3.192	-2.654	-2.744	-2.683	-2.723
Z [t-bar]	-3.883	-4.501	-4.485	-2.578	-2.602	-6.254	-2.461	-3.115	-2.587	-2.733	-5.970	-2.198	-2.833	-2.403	-2.686
p-value	0.000	0.000	0.000	0.005	0.005	0.000	0.007	0.001	0.005	0.003	0.000	0.014	0.002	0.008	0.004

CADF: test under the null hypothesis of non-stationarity. Critical value 0.10: -2.550, Critical value 0.05: -2.600, Critical value 0.01: -2.720.

sector in the economy. The results directly indicate that the service sector has the highest share in OECD economies, while the agricultural sector has the lowest share.

Our findings on the aggregate and sectoral EKC hypothesis are consistent with the findings of recent studies such as [Htike et al. \(2021\)](#), [Ferreira et al. \(2022\)](#) and contrary to the findings for the industrial sector in [Dogan and Inglesi-Lotz \(2020\)](#).

## 6 Conclusion and discussions

The OECD is responsible for more than half of greenhouse gas emissions, making it the largest group of greenhouse gas emitting countries. This paper first analyses the impact of energy consumption asymmetry on CO2 using the PNARDL model with panel data for four sectors and 38 OECD economies for the period 1990–2022. Secondly, this paper investigates the relationship between income level and CO2 emissions in the context of the EKC hypothesis.

Our empirical results show that the EKC model is valid when the income-emissions relationship and total CO2 are taken into account, but differences emerge at the sectoral level.

We conclude that it may not be appropriate to generalize by aggregating sectors and use these findings for policy formulation. Because, as it is understood from the findings, sector-specific characteristics such as energy requirement, technological progress, resource endowment differentiate the income-emission relationship of each sector.

The empirical evidence substantiates the existence of the EKC hypothesis across all sectors, with the exception of the industrial sector. This result points to policy options for shifting industrial policies towards more renewable energy sources and increasing the green capital stock in industry sector. Moreover, in the industrial sector, the underlying causes of elevated emissions levels must be identified and comprehensive environmental policies must be established to reinforce existing environmental regulation policies. Nevertheless, the results indicate that increased economic growth in the agricultural, manufacturing, and service sectors has the potential to contribute to improvements in environmental quality. It is, therefore, incumbent upon policymakers to devise policies that promote economic growth while concurrently improving environmental quality.

The utilisation of hybrid and electric motorised agricultural vehicles in the agricultural sector has the potential to reduce CO2 emissions. It is recommended that the government provide support for the research and development of energy-saving hybrid and electric motorised agricultural vehicles.

It is recommended that the government implement subsidies for renewable energy generation systems, with the objective of increasing the use of renewable energy in the manufacturing sector.

The services sector includes sub-sectors with high energy consumption. It is therefore recommended that energy-saving appliances and building materials be promoted in these sectors.

However, the findings of our study suggest that the energy consumption-CO2 relationship is asymmetric both in the short and long run.

When the countries on the positive side of the Kuznets curve are analyzed, it is seen that they are generally OECD countries with

TABLE 8 Cointegration test.

Test type	Model I (Agricul.)	Model II (Industry)	Model III (Manufac.)	Model IV (Service)	Model V (Total Econ.)
<i>Panel A: Pedroni Cointegration Test</i>					
Modified variance ratio	-6.3893*** [0.000]	-6.5274*** [0.000]	-6.4689*** [0.000]	-6.4460*** [0.000]	-6.3016*** [0.000]
Modified Phillips-Perron t	2.3443*** [0.009]	2.3997 *** [0.008]	1.7823** [0.037]	2.8123*** [0.002]	2.0510** [0.021]
Phillips-Perron t	-5.6023*** [0.000]	-5.9542*** [0.000]	-7.1764*** [0.000]	-6.0415*** [0.000]	-6.7119*** [0.000]
Augmented Dickey-Fuller t	-5.7178*** [0.000]	-6.4344*** [0.000]	-7.6218*** [0.000]	-6.7269*** [0.000]	-6.9003*** [0.000]
<i>Panel B: Westerlund Cointegration Test</i>					
Variance ratio	-1.5520* [0.060]	-1.3035* [0.096]	-2.0755** [0.019]	-1.5876 * [0.056]	-1.6457 * [0.049]

H<sub>0</sub>: No cointegration. Cointegrating vector: Panel specific. AR, parameter: Panel specific. Time trend: Included. Panel means: Included. probability values in brackets.

TABLE 9 JKS non-causality test.

Test statistics	Model I (Agriculture)	Model II (Industry)	Model III (Manufacture)	Model IV (Service)	Model V (Total Econ.)
<i>HPJ Wald test</i>	52.3195	42.1813	41.5510	53.7158	48.2580
<i>p-value</i>	0.000	0.000	0.000	0.000	0.000

H<sub>0</sub>: Selected covariates do not Granger-cause CO<sub>2</sub>. H<sub>1</sub>: H<sub>0</sub> is violated. Cross-sectional heteroskedasticity-robust variance estimation. Half Panel Jackknife (HPJ). Bootstrap Variances for HPJ, test (200).

TABLE 10 Panel ARDL regression with asymmetric effect.

Variables	Model I (Agriculture)	Model II (Industry)	Model III (Manufacture)	Model IV (Service)	Model V (Total Econ.)
<i>Long-run Coef</i>					
ln(en <sup>-</sup> )	1.305*** (0.0303)	1.311*** (0.0359)	1.331*** (0.0354)	1.168*** (0.0334)	1.207*** (0.0311)
ln(en <sup>+</sup> )	1.311*** (0.0305)	1.319*** (0.0360)	1.338*** (0.0356)	1.173*** (0.0335)	1.212*** (0.0313)
ln(k)	-0.260*** (0.0139)	-0.341*** (0.0299)	-0.290*** (0.0304)	0.0107 (0.0440)	-0.116*** (0.0443)
ln(pop)	-0.504*** (0.0538)	-0.396*** (0.0641)	-0.439*** (0.0661)	-0.258*** (0.0630)	-0.208*** (0.0638)
ln(gdp)	1.189*** (0.240)	-0.150 (0.301)	0.425** (0.170)	0.665*** (0.232)	1.141*** (0.260)
ln(gdp) <sup>2</sup>	-0.107*** (0.0209)	0.0140 (0.0184)	-0.0283** (0.0112)	-0.0522*** (0.0126)	-0.0686*** (0.0139)
<i>ect</i>	-0.352*** (0.0359)	-0.312*** (0.0303)	-0.311*** (0.0298)	-0.375*** (0.0308)	-0.348*** (0.0328)
<i>Speed of adj. (year)</i>	2.84	3.21	3.22	2.67	2.87
<i>Short-run Coef</i>					

(Continued on following page)

TABLE 10 (Continued) Panel ARDL regression with asymmetric effect.

Variables	Model I (Agriculture)	Model II (Industry)	Model III (Manufacture)	Model IV (Service)	Model V (Total Econ.)
$\Delta \ln(en^-)$	-0.364*** (0.0821)	-0.316*** (0.0654)	-0.325*** (0.0654)	-0.376*** (0.0588)	-0.344*** (0.0573)
$\Delta \ln(en^+)$	-0.367*** (0.0823)	-0.318*** (0.0655)	-0.327*** (0.0656)	-0.378*** (0.0589)	-0.345*** (0.0574)
$\Delta \ln(k)$	-0.385* (0.233)	-0.529** (0.245)	-0.175 (0.238)	-0.0349 (0.282)	-0.0121 (0.269)
$\Delta \ln(pop)$	-0.700 (0.874)	-0.740 (0.883)	-0.262 (0.868)	0.000653 (0.980)	0.204 (1.155)
$\Delta \ln(gdp)$	-5.985** (2.447)	-2.678 (4.064)	-2.435 (4.045)	-15.37*** (5.833)	-12.69** (5.923)
$\Delta \ln(gdp)^2$	0.457** (0.194)	0.149 (0.222)	0.160 (0.243)	0.782*** (0.284)	0.617** (0.276)
Constant	-1.375*** (0.152)	-0.438*** (0.0627)	-1.026*** (0.112)	-2.954*** (0.242)	-3.716*** (0.351)
Obs	1,216	1,216	1,216	1,216	1,216
id	38	38	38	38	38
t	32	32	32	32	32
Log likelihood	2492.123	2517.381	2546.884	2585.342	2590.051
EKC	yes	no	yes	yes	yes
Turning Point (per cap. USD)	697.94\$	-	2017.02\$	18,534.07\$	29,249.87\$

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

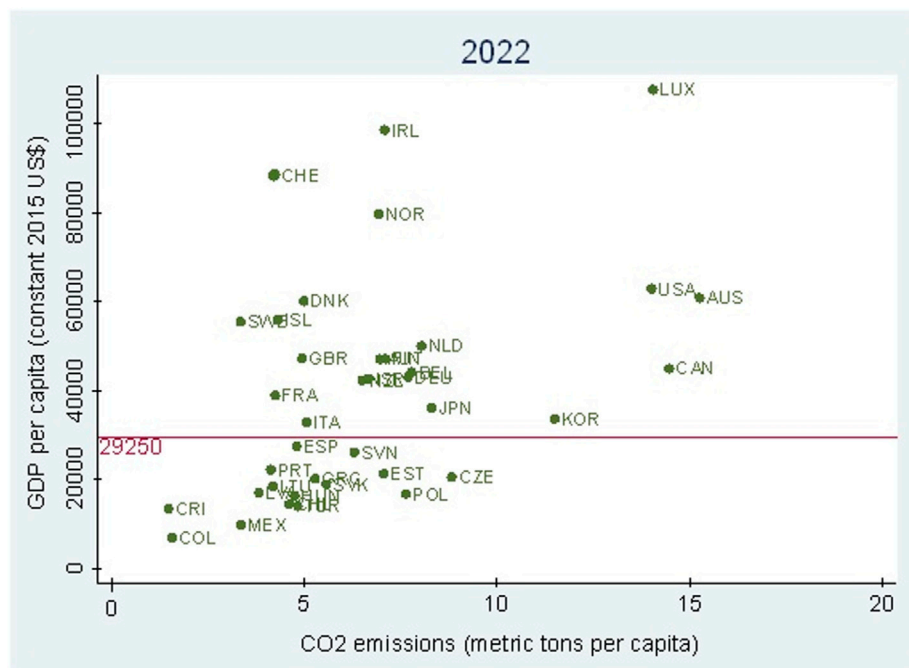
TABLE 11 Testing asymmetries.

Variables	Model I (Agriculture)	Model II (Industry)	Model III (Manufacture)	Model IV (Service)	Model V (Total Econ.)
<i>Panel A: Long-run asymmetries</i>					
$\ln(en)$	67.91*** [0.000]	58.94*** [0.000]	62.99*** [0.000]	55.27*** [0.000]	44.32*** [0.000]
<i>Panel B: Short-run asymmetries</i>					
$\ln(en)$	43.12*** [0.000]	37.05*** [0.000]	31.14*** [0.000]	33.38*** [0.000]	26.18*** [0.000]

\*\*\*, \*\*, and \* represent statistical significance at the 1%, 5%, and 10%, respectively. Probability values in brackets. Null Hypothesis  $H_0: \beta_1 = \beta_n$  (No long-run asymmetry).

relatively lower GDP *per capita*. These are generally the countries that left the Soviet Union (Slovakia, Slovenia, Estonia, Czech Republic, Poland, Croatia, etc.) and developing economies

(Türkiye, Mexico, Colombia). The findings show that for countries falling behind the turning point, policies to increase renewable energy resources, especially in the industrial sector, are



GRAPH 1  
Scatter plot of per capita GDP and CO2 for year 2022.

needed. It is necessary for OECD countries to restructure the industrial sector in an environmentally sustainable manner. For the sustainable development of the sector, its impact on the environment is crucial. Policies should be implemented to reduce CO<sub>2</sub> emissions by spending on R&D in this area, developing human capital in these sectors and improving the technical efficiency of production technology in the development of environmentally friendly technologies.

The reasons why the EKC hypothesis is not valid in the industrial sector and the individual dynamics of other sectors await further clarification in future studies.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

YM: Conceptualization, Data curation, Investigation, Methodology, Software, Supervision, Writing–original draft, Writing–review and editing. MS: Conceptualization, Data curation, Investigation, Methodology, Software, Writing–original draft, Writing–review and editing. EU: Conceptualization, Data curation, Investigation, Methodology, Software, Writing–original

draft, Writing–review and editing. DS: Conceptualization, Data curation, Investigation, Methodology, Software, Supervision, Writing–original draft, Writing–review and editing.

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