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The asymmetric effect of renewable and non-renewable energy on carbon emissions in OECD: new evidence from non-linear panel ARDL model

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The level of economic income, population density and sources of energy supply is critical in assessing environmental quality. Recent empirical studies paid limited attention to the role of renewable (RE) and fossil energy (NRE) supply in carbon pollution regarding the Environmental Kuznets Hypothesis (EKC). Therefore, this study investigates the asymmetric relationships between carbon emissions and energy sources on the one hand and the environmental Kuznets hypothesis on the other hand for OECD countries, comprising countries with significant renewable energy supplies. The study includes the annual data from 1990 to 2021 and performs panel non-linear ARDL regression. The empirical results clearly show that RE and NRE have asymmetric effects on emissions in the long run but not in the short run. Both positive and negative shocks in RE reduce CO_2 emissions in OECD economies, while asymmetric shocks in NRE substantially increase them. Increasing RE supply is clearly effective in reducing emissions. However, unlike most previous studies, this study shows that RE does not significantly reduce CO_2 emissions in OECD countries. The error correction term (ect.) in the NARDL model is negative and significant. The magnitude of the term indicates that the system will return to long-term equilibrium about 4.2 years after any shock. Furthermore, we show that the EKC Hypothesis is supported in OECD countries. The turning point of the EKC is at $4085.77 *per capita*. Besides, regression with Driscoll-Kraay standard errors and Augmented Mean Group (AMG) estimator approach were used for robustness checks. The findings from the robustness check are consistent with the NARDL findings. Policies based on the promotion of a low-carbon and sustainable green environment should place greater emphasis on renewable resources even in OECD countries. Moreover, while many studies in the literature address asymmetric effects and EKC as energy consumption or utilisation, the novelty of this study is that it approaches the issue regarding energy supply with asymmetric effects for RE and NRE.

KEYWORDS
carbon emissions, renewable energy, non-renewable energy, environmental kuznets curve, non-linear panel

1 Introduction

The industrial revolution in the 19th century transformed production processes and enabled the use of, energy in production. The industrialization of more and more countries has continued to increase rapidly in the world's energy production and consumption, especially in the last few decades. This has put enormous pressure on the ecological balance while providing safe protection for the development of human society (Song et al., 2021). Result of this pressure, the world has been exposed to various environmental problems such as environmental pollution, climate change and global warming (Ozcan et al., 2019; Mujtaba et al., 2020). Especially the large amount of carbon dioxide formed as a result of the use of fossil energy sources entered the atmosphere, causing an increase in the greenhouse effect (Ge et al., 2022). This, in turn, has increased climate problems by causing glaciers to melt, sea level rise, and desertification, abnormal weather conditions (Le Xu et al., 2021). Non-renewable energy, sources such as natural gas, coal, and oil are seen as the most important cause of environmental pollution and global warming (Gyamfi et al., 2021; Usman et al., 2022; Zhang et al., 2023). Under the assumption that nothing has been done about this problem, the probability of a 4°C increase in global temperatures is 75%, and the probability of an 8°C increase is 21% (Waldhoff and Fawcett, 2011). Such a temperature rise could upset the ecological balance of the planet. Considering that the global carbon dioxide emission reached its highest level in 2022 (IEA, 2022), it is necessity to urgently address and implement policies to reduce carbon emissions at the global level.

Renewable energy (such as solar, geothermal, wind, and biomass) can play an important role in reducing carbon emissions (Charfeddine and Kahia, 2019; Chien et al., 2022). Renewable energy sources are a clean alternative to energy sources with high carbon content as they do not release carbon dioxide when converted into energy (Anwar et al., 2021). These clean energy sources are recommended for the realization of production processes with environmental sustainability (Khan et al., 2020). Renewable energy sources, including hydropower and biomass, contribute approximately 17% of the world's overall energy demand while significantly reducing carbon dioxide emissions (Sun et al., 2022).

Grossman and Krueger (1991) is one of the first studies to examine the relationship between environmental pollution and economic growth. They concluded that carbon dioxide emissions increase with gross domestic product (GDP) *per capita* at lower national income levels, but environmental pollution decreases at higher income levels. Panayotou (1993); Cole et al. (1997) also confirmed this relationship. Thus, the relationship between environment and income is accepted as the Environmental Kuznets Curve (EKC) in the literature, based on the Kuznets Curve proposed by Kuznets (1955). According to the EKC hypothesis, there is an inverted U-shaped correlation between environmental quality and economic growth. With the increase in income, carbon emissions will increase up to a certain income "threshold" and then carbon emissions will tend to decrease. In this framework, the relationship between carbon emissions and economic growth under the EKC hypothesis has been the subject of many studies in the last 3 decades (Selden and Song, 1994; Lean and Smyth, 2010; Van Hoa and Limskul, 2013; Kais and Sami, 2016; Sinha et al., 2017; 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., 2023a).

According to various environmentalists, excessive energy use is the biggest contributor to environmental pollution and environmental degradation, complicating the validity of the EKC hypothesis. For this reason, countries encourage the use of renewable energy sources instead of non-renewable energy sources (Munir, 2022). On the other hand, as the income level increases, citizens will give more importance to environmental pollution and will force the sectors to use clean, that is, renewable energy sources (Xie et al., 2020). Since the production and consumption of renewable energy sources are environmentally friendly, it is also one of the important determinants of breaking the strong link between fuel pollution, CO_2 emissions and the growth of an economy (Balsalobre-Lorente and Leitao, 2020; Akadiri and Adebayo, 2022; Shahbaz et al., 2021; Banga et al., 2022; Sun et al., 2022). Therefore, diversification of renewable energy sources and renewable energy supply plays, an important role in reducing environmental and energy problems (Mert et al., 2019; Zaidi et al., 2019). In addition, renewable energy contributes to sustainable economic development (Apergis and Payne, 2010; Chen et al., 2020; Dogan et al., 2020; Ivanovski et al., 2021) and helps to stabilize both inflation and exchange rates (Deka and Dube, 2021; Deka et al., 2022; Mukhtarov et al., 2022).

Economic income level, population and energy supply are critical in assessing environmental quality. Under the EKC hypothesis, limited attention has been paid to the role of energy supply in carbon pollution. Therefore, unlike previous studies, this study examines the asymmetric relationships between carbon emissions and energy resources on the one hand, and the EKC hypothesis on the other hand, for Organisation for Economic Co-operation and Development (OECD) countries, which consist of countries with significant renewable energy resources. OECD countries have a significant share of the world economy. In 2019, the total GDP of the world was 84.7 trillion dollars. OECD countries have about 61% of this GDP value ($51.5 trillion) (WDI, 2023). CO_2 emissions in the world were 20.3 million kilotons in 1990 and reached 35.5 kilotons in 2019. However, a similar increase was not observed in OECD countries. That is, CO_2 emissions, which were 11.3 million kilotons in total in the OECD countries in 1990, reached 13.3 million kilotons in 2007 and decreased to 11.6 kilotons in 2019 (OECD, 2023). In 2020, when the COVID-19 pandemicbegan, CO_2 emissions fell sharply. By the end of 2020, containment measures related to COVID-19 had reduced emissions by about 7% below 2019 levels. The largest share of this decrease was due to transportation emissions (Le Quéré et al., 2021). Mousazadeh et al. (2021) identified several benefits during the first months of COVID-19 on carbon emissions in the atmosphere. Since electricity generation is considered to be one of the main causes of greenhouse gas emissions, public policies such as mandatory lockdown events during COVID-19 have likely reduced final electricity consumption. Thus, a potential reduction of greenhouse gases is expected. Previous research has also found that government regulations or containment policies in response to the outbreak of COVID-19 can significantly reduce air pollution and reduce CO_2 emissions (Abbas et al., 2021; Dang and Trinh, 2021). On the other hand, renewable energy supply is constantly increasing in OECD countries. While the renewable energy supply was 6.13% of the primary energy supply in 1990, this rate was 10.97% in 2019. All these statistics are of great importance for the study of OECD countries (OECD, 2023).

However, energy supply shocks are a different issue that needs to be analysed. The rapid increase in oil prices in the 1970s adversely affected the output levels of countries. This crisis is one of the best examples of supply shock in the economic literature. Similar types of supply shocks were encountered during the COVID-19 pandemic. The literature has generally focused on the relationship between energy supply and output level or the effect of energy consumption on CO_2 emissions. In this study, unlike other studies, we tried to determine the effect of positive and negative shocks in energy supply on CO_2 emissions. Another feature that distinguishes this study from other studies is that we investigate the positive and negative effects of both renewable and non-renewable energy supply. For this purpose, we had to use a non-linear method to adjustment of the variables from short-run to long-run equilibrium. We also used the nonlinear ARDL approach of Shin et al. (2014) to identify the positive and negative effects of energy supply shocks. In order to make a comprehensive analysis, we included OECD countries in our analysis. Because OECD countries cover 61% of the world GDP and OECD countries have almost doubled the renewable energy supply in total energy supply in the last 30 years. In this context, annual data from 1990 to 2021 for OECD countries were used in the study, and the analyzes were performed with panel nonlinear ARDL regression, unlike previous studies. In addition, Driscoll-Kraay standard errors and Augmented Mean Group (AMG) estimator were used to check the robustness of the findings.

The remainder of this study is structured as follows. The relevant literature review is presented in Section 2. Section 3 describes the economic framework, econometric methodology, dataset and model used in the study. In section 4, we present the empirical results. Section 5 concludes the article by discussing the findings.

2 Literature review

Green House Gases (GHGs) are major environmental degradation factors and these factors affect the population's health directly. One of the reasons of environmental degradation is energy consumption and the main reason of energy consumption is production. Governments aim to develop their economy and increase their output, etc. Both renewable and non-renewable energy resources play a vital role in economic development. Whereas non-renewable energy use is one of the reasons of greenhouse gases, renewable energy use is a critical component of combating global climate change (Uğurlu, 2019; 2022), reducing greenhouse gas emissions.

Because of this relationship, there is a wide literature to investigate the relationship GHGs and renewable or non-renewable energy sources. In this paper we estimate a non-linear model to estimate the relationship, that is why we mainly focus on papers which use non-linear models. Following paragraph, the presented papers show that in the literature different kinds of data (cross-section, time series, panel data) and different kinds of models are used.

Renewable and non-renewable energies are not the only source of GHGs. There are many papers which investigate the relationship between deagriculturalization, financial development and financial development data, etc. (Lin et al., 2022) study the impact of agriculturalization on CO_2 emissions by testing symmetric and asymmetric impact for the selected Asian countries using data from 1985 to 2019 (Boufateh and Saadaoui, 2020). investigates asymmetric financial development shocks on CO_2 emissions; the paper uses a nonlinear panel ARDL–PMG model for a panel of 22 African countries over the period of 1980-2014 (Koondhar et al., 2021). investigate asymmetric causality connection between energy use in agriculture for Pakistan using data period of 1976-2018 (Li X. et al., 2022). estimate panel linear and nonlinear autoregressive distributed lag models with the PMG and MG estimators to assess the financial deepening index's impact on carbon emissions of BRIC countries for the period of 1990-2019 (Xu et al., 2022). dealt with G7 countries to examine the non-linear and asymmetric relationship between reorientation in financial development and renewable energy generation process which ensures environmental sustainability between renewable energy and CO_2 emissions between 1986 and 2019.

Similar to our paper (Zaidi et al., 2018), and (Anwar et al., 2021) investigate renewable and non-renewable energy; whereas we use energy supply they use energy consumption (Onuoha et al., 2022), investigate both renewable and non-renewable energy sources (they used fossil fuel data) in relation to the EKC hypothesis for 15 ECOWAS[1] countries by estimating the PNARDL model (Zaidi et al., 2018). estimate ARDL model for Pakistan from 1970 to 2016 (Anwar et al., 2021), estimate Fully Modified Ordinary Least Square (FM-OLS), Dynamic-OLS and Fixed-Effect-OLS models for ASEAN economies from 1990 to 2018 (Toumi and Toumi, 2019). use the NARDL model by using renewable energy, carbon dioxide emissions, and real GDP variables of the Kingdom of Saudi Arabia between 1990 and 2014 (Munir and Riaz, 2019). examines relationship of energy consumption and environmental quality (CO_2 emissions) in three South Asian countries (Bangladesh, India, and Pakistan) from 1985 to 2017. The authors use the PARDL model and estimate the model separately for each energy source such as oil, coal, gas, and electricity consumption (Akram et al., 2020). assess asymmetric impacts of energy efficiency and renewable energy, and other factors on CO_2 emissions in BRICS (i.e., Brazil, Russia, India, China, and South Africa) countries from 1990 to 2014 (Mosikari and Eita, 2020). test the EKC for the period 2005–2019 from 29 selected African countries by using the panel smooth transition regression (PSTR) technique (Kartal et al., 2022). use monthly data to estimate the asymmetric effect of electricity consumption on carbon dioxide in the United States, by collecting monthly data from January 1973 to November 2021 (Akadiri and Adebayo, 2022). uses ARDL model to capture relation between CO_2 emissions and renewable energy consumption and non-renewable energy consumption in India employing a dataset from 1970 to 2018 (Munir, 2022). aim to show existence of nonlinear effect of energy use on CO_2 emissions by using NARDL model for 21 EU countries from 1990 to 2018 (Akram et al., 2022). select MINT countries (Mexio, Indonesia, Nigeria and Turkey) to investigate energy efficiency and renewable energy impact on CO_2 emissions in

1 Benin, Burkina Faso, the Gambia, Guinea, Guinea-Bissau, Liberia, Mali, Niger Republic, Sierra Leone, Togo, Cabo-Verde, Cote d'Ivoire, Ghana, Nigeria, and Senegal.

1990–2014) (Mujtaba et al., 2022a). use data over the period 1971-2014 to see the impact of economic growth, energy consumption, and population (POP) on CO_2 emissions in the five regions[2] (Majeed et al., 2022). address the effect of nuclear energy on CO_2 emissions for Pakistan from 1974 to 2009 by using ARDL and NARDL models (Qamruzzaman, 2022). considers 30 nations from low-income countries and 38 Lower-Middle-Income countries to investigate the renewable energy carbon emission relationship from a different perspective by using renewable energy used in agricultural activities from 1985 to 2019 (Zhang et al., 2022). select institutional factors, GDP *per capita*, energy consumption, and foreign direct investment of BRICS countries (Brazil, Russia, India, China, and South Africa) to test the asymmetric effect of the variables on CO_2 emissions by using the Panel ARDL-PMG model from 1996 to 2019 (Iqbal et al., 2022). states that some natural resources can add to the current stock of CO_2 emissions and hurt the environmental quality, therefore the authors use natural resources, and economic progress in their research model which aims to analyze the asymmetric relationship between renewable energy production and CO_2 emission in Pakistan from 1980 to 2019 (Caglar et al., 2022). collected data from BRICS countries to investigate the relation between CO_2 emissions and renewable energy with some other control variables which are foreign direct investments, and natural resources. In the empirical section, balanced data was used in the NARDL model; 1992-2018 data for Russia, and 1980-2018 data rest of the BRICS countries (Sun et al., 2020). compare OECD and Belt and Road (B&R) countries over the period 1992-2015 based on their energy consumption, trade openness, urbanization and CO_2 emission relationship by estimating panel common correlated effects mean group (CCEMG) and augmented Mean Group (AMG) estimators (Rahman et al., 2022). claim that although economic growth has increased in 22 well-developed countries the level of CO_2 emissions has decreased. Based on this idea the authors aim to examine the affected factors of CO_2 emission which are renewable energy, technological innovation and export quality. To do this examination they use 22 selected countries[3] and estimate the NARDL model for the period 1990-2018 (Saqib, 2022; Saqib et al., 2022). investigate asymmetric linkages between renewable energy, technological innovation, and carbon-dioxide emission and EKC hypothesis in the context of renewable energy; the first paper uses NARDL for 18 developed economies[4] and the second paper use cross-sectional augmented autoregressive distributive lag (CS-ARDL), Augmented Mean Group (AMG), and Dumitrescu Hurlin causality tests for E7 economies[5] (Adebayo et al., 2023). use cointegration test and NARDL and addition they use Dynamic Multiplier and Spectral Causality for Turkey.

(Li et al., 2021; Li et al., 2022a; Li et al., 2022b; Wang et al., 2023b) are the some of the lastest panel data studies about relationship between carbon emissions and economic factors (Wang et al., 2023a).is one of the panel data stuies and generally confirm the EKC; in 2018, 72 countries of 208 countries reached the EKC turning point for *per capita* income. In (R. Li et al., 2021) investigated 147 countries consist of different income groups and the results show that the lower middle income group countries have mostly bidirectional causality, while the lower middle income group coountries have unidirectional relationship between energy structure and the selected variables (Wang et al., 2022). focus on urbanization and claim that trade openness and natural resource rents increase environmental pressure, population aging and renewable energy decrease environmental pressure (Li et al., 2022b). presents new perspective the 3E model, and assert that negative effect of renewable energy on the ecological footprint first weakens and then increases with the increase of urbanization (Li et al., 2022a). is the another panel data paper but use provinces of China instead of world countries. The authors find that that the decoupling between income growth and CO2 in the Chinese transport sector is particularly poor.

Dilanchiev et al. (2023) proves that relationship between renewable energy production and GDP *per capita* and is significant and negative in Romania, Azerbaijan, Russia, Turkey, Bulgaria, and Greece. Sun et al. (2020) investigate relationship between natural resource rent (NRR) management, green technology innovation (GTI), and GDP growth and the results show that NRR and GTI decrease carbon emission. Asif et al. (2023) use questionaire to collect data and estimate structural equation modelling for the analysis and the findings show that awareness of environmental factors and a positive attitude support to consumers adopting renewable energy.

Some of the research which are mentioned above are confirmative to each other results but some of them are contradictory (Toumi and Toumi, 2019). find that in the long run, the asymmetric causal connection between carbon dioxide emissions and renewable energy is neutral, and both positive and negative shocks on renewable energy consumption have an adverse impact on CO_2 emissions. The results of (Kartal et al., 2022) show the important asymmetric effect on CO_2 emission from different kinds of electricity consumption (residential, commercial, industrial and transportation) and they are very important factors to protect the environmental quality of the United States. (Adebayo et al., 2023) assert that positive (negative) shocks in renewable energy usage and a positive shock in structural change decrease emission levels in Turkey (Akram et al., 2020). find that positive shocks in energy efficiency and fluctuation in the positive component of renewable energy reduce CO_2 emissions (Saqib, 2022). recognize that renewable energy is a significant variable to reduce CO_2 emissions (Saqib et al., 2022). supports the result of renewable energy decreasing the effect on environmental degradation (Akadiri and Adebayo, 2022).'s estimations show a negative relationship between renewable energy consumption and carbon emissions in India. The PSTR technique, in the research of (Mosikari and Eita, 2020), indicates that in both regimes, energy consumption has an increasing effect on carbon emissions that is why African countries should reduce their non-renewable energy sources (Sun

2 East Asia, Latin America and the Caribbean, North America, as well as the Middle East and North Africa.

3 Australia, Austria, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Germany, Hungary, Ireland, Netherlands, Portugal, Romania, Slovakia, Spain, Sweden, Switzerland, Ukraine, United Kingdom, United States, and Uzbekistan.

4 Australia, Austria, Belgium, Finland, France, Germany, Hungary, Ireland, Italy, Japan, Luxembourg, Netherlands, Portugal, Spain, Sweden, Switzerland, United Kingdom, and United States.

5 Brazil, China, India, Indonesia, Russia, Mexico and Turkey.

et al., 2020). and (Munir and Riaz, 2019) show that energy usage has a nonlinear connection with CO_2 emissions. Also (Munir, 2022), estimates a non-linear model and finds coal, oil, gas and electricity consumption increases CO_2 emissions (Caglar et al., 2022).'s results show contradictory results which show a positive insignificant impact on CO_2 emission from renewable energy consumption; the authors state that the reason for insignificant impact is renewable energy consumption has not reached the considered level in BRIC countries. Moreover (Rahman et al., 2022) find that technological innovation and renewable energy use are valid ways to reduce carbon emissions.

3 Empirical methodology

This study aims to examine the Environmental Kuznet Curve (EKC) hypothesis in OECD countries by adding asymmetric effects of energy supply components on CO_2 emissions. Our main objective is to address, for the first time in the literature, the effects of asymmetric components of energy supply on CO_2 emissions in OECD. For this purpose, we use a nonlinear empirical framework and build an asymmetric panel ARDL model, to identify the impact of energy supply components on CO_2 in OECD countries, based on the nonlinear ARDL approach of Shin et al. (2014). Moreover, the adaptation of the EKC hypothesis test with asymmetric effects for the OECD constitutes the empirical infrastructure of the study. In addition, population density is included in the model to eliminate the possible effects of country size.

3.1 Economic framework

Energy demand and supply are highly vulnerable to external shocks. At the same time, energy is the main sub-input of production, and fossil resources are the main element of environmental pollution. In parallel with the development of econometric methods, it has become necessary to analyse asymmetric relationships rather than symmetric ones by considering this situation in the recent literature.

The EKC hypothesis is used to estimate the relationship between the environment and economic growth. According to the EKC hypothesis, an increase in energy consumption will increase economic growth and a further increase in energy consumption causes environmental degradation.

The economic theory on which this paper is based is the EKC hypothesis. Moreover, this study uses the EKC hypothesis to explore the non-linear relationship between the environment and energy supply. In order to find this relationship, the energy supply is decomposed into non-renewable and renewable energy supply components. In order to explain CO_2 emissions in OECD countries, we constructed the model as shown in Eq. 1.

$$CO2_{it} = \beta_{0i} + \beta_{1i}RE_{it} + \beta_{2i}NRE_{it} + \beta_{3i}GDP_{it} + \beta_{4i}GDP^2_{it} + \beta_{5i}POPD_{it} + \mu_{it} \tag{1}$$

where β_{0i} is the country fixed effect, $CO2_{it}$ is the logarithm of carbon dioxide emissions, GDP_{it} is the logarithm of real gross domestic product *per capita*, REN_{it} is the logarithm of renewable energy supply, $NREN_{it}$ is the logarithm of non-renewable energy supply, $POPD_{it}$ is the logarithm of population density and μ_{it} is an independently and normally distributed error term.

When the EKC hypothesis is considered theoretically and the empirical literature is analysed, it is expected that the sign of the elasticity of CO_2 emissions, with respect to gdp *per capita* will be positive ($\beta_3 > 0$), the elasticity with respect to the square of gdp *per capita* will have a negative sign ($\beta_4 < 0$), the elasticity of non-renewable energy supply will be positive ($\beta_2 > 0$), the elasticity of renewable energy supply will be negative, ($\beta_1 < 0$) and the elasticity of population density will be positive, ($\beta_5 > 0$).

3.2 Econometric approach

The method used in this study is the nonlinear panel ARDL method. There are different type of panel data models such as AMG (augmented mean group) estimator to calculate long-run parameters (Ali et al., 2023) This approach is based on the dynamic representation of heterogeneous panel data with the presence of asymmetry, following Shin et al. (2014). There are two reasons why we use this econometric approach. The first reason is to capture the asymmetric effects of renewable and non-renewable energy supply on CO_2 separately. The second reason is that the panel ARDL approach, which can be used in non-stationary panels, is also suitable for capturing the short-term dynamics of variables and their adjustment to long-run equilibrium. In this study, firstly the linear panel ARDL approach will be emphasised and then the non-linear panel ARDL approach will be explained.

3.2.1 The linear panel ARDL

The linear panel ARDL approach was introduced by Pesaran et al. (1996; 2001). The nonlinear panel ARDL approach is an extension of the linear panel ARDL approach. In this respect, it is more appropriate to first explain the linear panel ARDL approach. According to Pesaran et al. (1996; 2001), the linear panel ARDL representation could be formulated as in Eq. 2.

$$\begin{aligned}\Delta CO2_{it} = {} & \alpha_i + \gamma_{1i}CO2_{i,t-1} + \gamma_{2i}RE_{i,t-1} + \gamma_{3i}NRE_{i,t-1} + \gamma_{4i}GDP_{i,t-1} \\ & + \gamma_{5i}GDP^2_{i,t-1} + \gamma_{6i}POPD_{i,t-1} + \sum_{j=1}^{p_1}\delta_{1ij}\Delta CO2_{i,t-j} \\ & + \sum_{j=1}^{p_2}\delta_{2ij}\Delta RE_{i,t-j} + \sum_{j=1}^{p_3}\delta_{3ij}\Delta NRE_{i,t-j} \\ & + \sum_{j=1}^{p_4}\delta_{4ij}\Delta GDP_{i,t-j} + \sum_{j=1}^{p_5}\delta_{5ij}\Delta GDP^2_{i,t-j} \\ & + \sum_{j=1}^{p_6}\delta_{6ij}\Delta POPD_{i,t-j} + \varepsilon_{it}\end{aligned} \tag{2}$$

where Δ is the first difference operator, α_i is the constant term. The short-run coefficients are denoted by δ_{sij} ($s = 1, 2, 3, 4, 5, 6$), while the long-run coefficients are denoted by γ_{ki} ($k = 1, 2, 3, 4, 5, 6$) and the error term is denoted by ε_{it}. 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. Eq. 2 could be reformulated as in Eq. 3 by adding an error correction term.

$$\Delta CO2_{it} = \varphi_i + \sum_{j=1}^{p_1} \delta_{1ij} \Delta CO2_{i,t-j} + \sum_{j=1}^{p_2} \delta_{2ij} \Delta RE_{i,t-j} + \sum_{j=1}^{p_3} \delta_{3ij} \Delta NRE_{i,t-j} + + \sum_{j=1}^{p_4} \delta_{4ij} \Delta GDP_{i,t-j} + \sum_{j=1}^{p_5} \delta_{5ij} \Delta GDP^2_{i,t-j} + \sum_{j=1}^{p_6} \delta_{6ij} \Delta POPD_{i,t-j} + \lambda_i ect_{i,t-1} + \varepsilon_{it} \quad (3)$$

where the linear error correction term is denoted by $ect_{i,t-1}$. λ_i is the parameter which indicates the speed of error correction in the model's adjustment to equilibrium.

However, it is not appropriate to use a linear panel ARDL model when investigating the presence of asymmetric relationships between variables. In such cases, it is more appropriate to use the asymmetric panel ARDL method developed by Shin et al. (2014). The purpose of constructing the nonlinear model is to detect short and long-term asymmetric movements with the help of the asymmetric error correction model.

3.2.2 The nonlinear panel ARDL

The difference of the non-linear panel ARDL model from the linear panel ARDL model is that it allows for asymmetric responses of CO_2 emissions to renewable and non-renewable energy supply. In the nonlinear panel ARDL approach, the exogenous fluctuating variable is decomposed into two partial sums. In our model, the exogenous fluctuating variables are $RE_{i,t}$ and $NRE_{i,t}$. $\Delta RE^+_{i,t}$ is the positive partial sum expected to capture the upward fluctuations of $RE_{i,t}$, while $\Delta RE^-_{i,t}$ is the negative partial sum expected to capture the negative changes of $RE_{i,t}$ and, $\Delta NRE^+_{i,t}$ denotes the positive partial sum expected to capture the upward fluctuations, while $\Delta NRE^-_{i,t}$ denotes the negative partial sum expected to capture negative changes of $NRE_{i,t}$. The basic idea here is that positive and negative shocks to renewable and non-renewable energy supply are expected to have different effects on CO_2 emissions.

$$\begin{aligned} REN^+_{i,t} &= \sum_{j=1}^{t} \Delta RE^+_{i,j} = \sum_{j=1}^{t} \max\left(\Delta RE^+_{i,j}, 0\right) \\ REN^-_{i,t} &= \sum_{j=1}^{t} \Delta RE^-_{i,j} = \sum_{j=1}^{t} \min\left(\Delta RE^-_{i,j}, 0\right) \\ NREN^+_{i,t} &= \sum_{j=1}^{t} \Delta NRE^+_{i,j} = \sum_{j=1}^{t} \max\left(\Delta NRE^+_{i,j}, 0\right) \\ NREN^-_{i,t} &= \sum_{j=1}^{t} \Delta NRE^-_{i,j} = \sum_{j=1}^{t} \min\left(\Delta NRE^-_{i,j}, 0\right) \end{aligned} \quad (4)$$

In this paper, a nonlinear panel ARDL model is constructed by adding short-term and long-term asymmetric relationships to the linear panel ARDL model specified in Eq. 4 The model estimated in the study is shown in Eq. 5

$$\Delta CO2_{it} = \eta_i + \gamma_{1i} CO2_{i,t-1} + \gamma^+_{2i} RE^+_{i,t-1} + \gamma^-_{2i} RE^-_{i,t-1} + \gamma^+_{3i} NRE^+_{i,t-1} + \gamma^-_{3i} NRE^-_{i,t-1} + \gamma_{4i} GDP_{i,t-1} + \gamma_{5i} GDP^2_{i,t-1} + \gamma_{6i} POPD_{i,t-1} + \sum_{j=1}^{p_1} \delta_{1ij} \Delta CO2_{i,t-j} + \sum_{j=1}^{p_2} \left(\delta^+_{2ij} \Delta RE^+_{i,t-j} + \delta^-_{2ij} \Delta RE^-_{i,t-j}\right) + \sum_{j=1}^{p_3} \left(\delta^+_{3ij} \Delta NRE^+_{i,t-j} + \delta^-_{3ij} \Delta NRE^-_{i,t-j}\right) + \sum_{j=1}^{p_4} \delta_{4ij} \Delta GDP_{i,t-j} + \sum_{j=1}^{p_5} \delta_{5ij} \Delta GDP^2_{i,t-j} + \sum_{j=1}^{p_6} \delta_{6ij} \Delta POPD_{i,t-j} + \varepsilon_{it} \quad (5)$$

While the long-term asymmetric response of CO_2 to positive and negative shocks on renewable energy supply is estimated from the coefficients γ^+_{2i} and γ^-_{2i}, the short-term asymmetric response is obtained from the coefficients δ^+_{2ij} and δ^-_{2ij}.

The long-term and short-term asymmetric response of CO_2 to positive and negative shocks on non-renewable energy supply is estimated with the coefficients γ^+_{3i} , γ^-_{3i} and δ^+_{3ij}, δ^-_{2ij} respectively. The asymmetric error correction term is shown in Eq. 6.

$$\Delta CO2_{it} = \tau_i + \sum_{j=1}^{p_1} \delta_{1ij} \Delta CO2_{i,t-j} + \sum_{j=1}^{p_2} \left(\delta^+_{2ij} \Delta RE^+_{i,t-j} + \delta^-_{2ij} \Delta RE^-_{i,t-j}\right) + \sum_{j=1}^{p_3} \left(\delta^+_{3ij} \Delta NRE^+_{i,t-j} + \delta^-_{3ij} \Delta NRE^-_{i,t-j}\right) + \sum_{j=1}^{p_4} \delta_{4ij} \Delta GDP_{i,t-j} + \sum_{j=1}^{p_5} \delta_{5ij} \Delta GDP^2_{i,t-j} + \sum_{j=1}^{p_6} \delta_{6ij} \Delta POPD_{i,t-j} + \theta_i ect'_{i,t-1} \varepsilon_{it} \quad (6)$$

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

3.3 Data set and model construction

The panel data set constructed in this study is the annual data of 38 OECD countries between 1990 and 2021. OECD countries are selected due to the high share of renewable energy supply in these countries.

Following the collapse of the Soviet Union in 1990, many countries' geographical and political borders, now members of the EU and OECD, have changed. To avoid excluding these countries from the data set, the period started in 1990.

Another important reason for constructing the data set from OECD countries is that they have similar structures in terms of economic and social conditions compared to other country groups. In addition, since these countries are advanced in terms of institutional infrastructure, the data they provide are reliable.

The variables that should be included in the data set were determined by following the studies in the literature section.

The series are transformed into natural logarithms to reduce the variance in economic variables and to avoid heteroskedasticity and spurious regression results. The definitions, units and sources of the variables used in the empirical analysis are shown in Table 1.

The economic model adopted in this paper relates not only to the asymmetric impact of energy supply components on CO_2 but also to the specification of the EKC hypothesis. Following the theoretical foundation of the NARDL model, the model illustrates the long-run asymmetric linkages between renewable (RE) and non-renewable energy supply and CO_2 emissions, controlling for the effects of population density. Eq. 7 represents the estimated econometric model.

$$\ln(CO2)_{it} = \beta_0 + \beta_1 \ln(RE^+)_{it} + \beta_2 \ln(RE^-)_{it} + \beta_3 \ln(NRE^+)_{it} + \beta_4 \ln(NRE^-)_{it} + \beta_5 \ln(GDP)_{it} + \beta_6 \ln(GDP)^2_{it} + \beta_7 \ln(POPD)_{it} + \varepsilon_{it} \quad (7)$$

We used the econometric software Stata 17.0 in our study. Indeed, the Stata commands and data set used in this study is an open request to other researchers.

TABLE 1 Variable descriptions.

Variables	Definition	Unit	Source
CO2	Carbon dioxide emission	Metric tons *per capita*	World Bank database
RE^+	Renewable energy supply increase	Ton of oil equivalent (toe) *per capita*	Authors' own calculation from OECD Energy database
RE^-	Renewable energy supply decrease	Ton of oil equivalent (toe) *per capita*	Authors' own calculation from OECD Energy database
NRE^+	Non-renewable energy supply increase	Ton of oil equivalent (toe) *per capita*	Authors' own calculation from OECD Energy database
NRE^-	Non-renewable energy supply decrease	Ton of oil equivalent (toe) *per capita*	Authors' own calculation from OECD Energy database
GDP	Real Gross Domestic Product	Constant 2015 US$ *per capita*	World Bank database
GDP^2	Real Gross Domestic Product squared	Constant 2015 US$ *per capita*	Authors' own calculation from World Bank database
POPD	Population Density	Number of human inhabitants per square kilometer	Authors' own calculation from World Bank population and area data

TABLE 2 Descriptive statistics of variables.

Variable	N	Mean	Sd	Variance	Cv	Se (Mean)	Skewness	Kurtosis	Min	Max
ln (CO2)	1140	1.961	0.589	0.346	0.300	0.017	−0.734	4.043	−0.094	3.413
ln (RE^+)	1216	−0.811	1.101	1.212	−1.358	0.032	−0.328	3.400	−4.643	2.793
ln (RE^-)	1216	−0.327	0.850	0.723	−2.597	0.024	−1.528	7.500	−4.793	2.772
ln (NRE^+)	1216	0.487	0.671	0.450	1.377	0.019	0.600	2.277	−1.155	2.230
ln (NRE^-)	1216	0.509	0.647	0.419	1.271	0.019	0.538	2.198	−0.984	2.216
ln (GDP)	1176	10.111	0.761	0.579	0.075	0.022	−0.428	2.325	8.214	11.630
ln $(GDP)^2$	1176	102.815	15.158	229.780	0.147	0.442	−0.297	2.251	67.476	135.256
ln (POPD)	1216	4.234	1.297	1.683	0.306	0.037	−0.812	3.278	0.798	6.254

4 Empirical findings

We began analysing the empirical findings with the summary statistics of the variables and their correlation linkages. The tables below define the variables respectively.

Table 2 shows that the highest standard deviation value is the standard deviation of population density, followed by the series of increased and decreased RE. This ranking is not surprising because population density is affected by the country's area and the total population. Therefore, it reflects the geographical scale of countries. On the other hand, renewable energy supply is sensitive to weather conditions as it includes climatic features such as solar and wind. The volatility and standard deviation of carbon emissions, GDP and NRE supply series are relatively stable.

The correlation coefficients between primary energy supply (renewable and non-renewable) and CO_2 emissions are statistically significant and range between 6% and 49%. GDP variables exhibit a highly positive and significant relationship between energy supply indicators and CO_2 emissions. Table 3 summarizes correlation relations.

The first step of the empirical investigation started with the cross-sectional dependency (CSD) analysis, as it should be considered when conducting other analyses. Pesaran (2004) CD test is used in this study to examine the cross-sectional correlation between variables. CSD test statistics are presented in Table 4.

Autocorrelation and heteroskedasticity tests were applied to ensure the reliability of the results. The statistics from the residual diagnostic tests are presented in Table 5. The findings suggest that the null hypotheses should be rejected for both tests.

The CADF unit root test results are presented in Table 6 and show that all series for OECD are non-stationary. When the first differences are taken, they become stationary with a 5% significance level. The findings show that the series are I (1).

Table 7 shows the Pedroni (1999); Pedroni (2004) and Westerlund's (2005) cointegration test statistics. The result indicates that lung run relationships exist among variables. Following Levin et al. (2002) algorithm, cross-sectional means were removed from the series to mitigate the impact of cross-sectional dependence. The Pedroni test statistics presented in the table reject the null hypotheses at the 1% significance level and indicate cointegration for the long run, and Westurlund test statistics indicate at 10%.

Causality relationships were investigated with the Juodis, Karavias and Sarafidis (2021). In general, this novel methodology developed by Juodis et al. (2021) offers several advantages, such as overcoming the "Nickell" bias, allowing cross-sectional dependence, and being suitable for

TABLE 3 Pairwise correlations.

Variables	ln (CO2)	ln (RE^+)	ln (RE^-)	ln (NRE^+)	ln (NRE^-)	ln (GDP)	ln $(GDP)^2$	ln (POPD)
ln (CO2)	1.000							
ln (RE^+)	−0.113***	1.000						
	(0.000)							
ln (RE^-)	0.058**	−0.284***	1.000					
	(0.049)	(0.000)						
ln (NRE^+)	0.469***	−0.074**	−0.027	1.000				
	(0.000)	(0.010)	(0.344)					
ln (NRE^-)	0.391***	−0.010	0.106***	−0.572***	1.000			
	(0.000)	(0.733)	(0.000)	(0.000)				
ln (GDP)	0.642***	0.161***	0.234***	0.257***	0.384***	1.000		
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)			
ln $(GDP)^2$	0.634***	0.165***	0.233***	0.249***	0.384***	0.999***	1.000	
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)		
ln (POPD)	−0.018	−0.532***	−0.245***	−0.009	0.022	−0.028	−0.032	1.000
	(0.547)	(0.000)	(0.000)	(0.746)	(0.434)	(0.346)	(0.266)	

Notes: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

TABLE 4 Cross sectional dependency test results.

Variable	CD-test	*p*-value	Mean (ρ)	Mean abs(ρ)
ln (CO2)	33.347	0.000	0.230	0.510
ln (RE^+)	13.976	0.000	0.090	0.190
ln (RE^-)	7.771	0.000	0.050	0.160
ln (NRE^+)	22.019	0.000	0.150	0.210
ln (NRE^-)	23.229	0.000	0.150	0.200
ln (GDP)	130.241	0.000	0.900	0.900
ln $(GDP)^2$	130.041	0.000	0.900	0.900
ln (POPD)	67.344	0.000	0.450	0.850

Notes: CD, test H0: Cross-section independence, CD ~ N (0,1). *p*-values close to zero indicate data are correlated across panel groups. ρ: Correlation coefficient.

TABLE 5 Residual diagnostic.

Test type	Test statistics	*p*-value
Wooldridge test for autocorrelation	39.259	0.000
Modified Wald test for groupwise heteroskedasticity	14,065.12	0.000

Notes: Wooldridge test H0: No first order autocorrelation. Modified Wald test H0: homoskedasticity.

homogeneous and heterogeneous panels. Granger non-causality test and the statistics are presented in Table 8.

The test statistics for all models indicate that the null hypothesis cannot be rejected and, therefore there exists a Granger causality relationship among the variables.

To assess the asymmetric effects of RE-NRE on CO_2 and to test the EKC hypothesis (see Eq. 1), we estimate panel nonlinear autoregressive distributed lag (PNARL) coefficients using the algorithm of proposed Shin et al. (2014). The findings are presented in Table 9.

TABLE 6 CADF unit root test results.

Variables	ln (CO2)	ln (RE^+)	ln (RE^-)	ln (NRE^+)	ln (NRE^-)	ln (GDP)	ln $(GDP)^2$	ln (POPD)
Panel A: Level								
t-bar	1.903	−2.218	2.116	−2.464	−2.459			−1.753
Z [t-bar]	2.696	0.853	1.572	−0.867	−0.831	1.832	2.103	4.114
p-value	0.996	0.803	0.942	0.193	0.203	0.967	0.982	1.000
Panel B: First Differences								
t-bar	2.718	−2.894	3.024	−3.876	−3.872			−2.577
Z [t-bar]	−2.707	−3.881	−4.795	−10.758	−10.732	2.219	−2.146	−1.771
p-value	0.003	0.000	0.000	0.000	0.000	0.013	0.016	0.038

Notes: CADF, test under the null hypothesis of non-stationarity. Critical value 0.10: −2.540, Critical value 0.05: −2.610, Critical value 0.01: −2.730.

TABLE 7 Cointegration test.

Test type	Statistics	*p*-value
Panel A: Pedroni Cointegration Test		
Modified Phillips-Perron t	5.016	0.000
Phillips-Perron t	−6.260	0.000
Augmented Dickey-Fuller t	−6.814	0.000
Panel B: Westerlund Cointegration Test		
Variance ratio	−1.452	0.073

Notes: H_0: No cointegration. Cointegrating vector: Panel specific. AR, parameter: Panel specific. Time trend: Included. Panel means: Included.

TABLE 8 JKS non-causality test.

Test statistics	Model I	Model II	Model III	Model IV	Model V
HPJ Wald test	4.8547	3.1589	4.5755	7.5326	6.5788
p-value	0.1828	0.3678	0.4698	0.2744	0.4740

Notes: H_0: Selected covariates do not Granger-cause CO_2. H_1: H_0 is violated. Cross-sectional heteroskedasticity-robust variance estimation. Half Panel Jackknife (HPJ).

Since one of the most important objectives of the study is to examine long-run asymmetries, Table 10 presents the results of the Wald test for the validity of these relationships. According to the Wald statistic for asymmetry, the null hypothesis is rejected for the long-run coefficient of non-renewable energy in model 5. The findings show that there is a valid asymmetric effect for non-renewable energy in the long run. In the short run, no such relationship is detected.

We will first interpret the findings of Model 5 and the other models can be interpreted by readers using the same logic. The error correction term (ECT), which indicates the cointegration relationship between the variables and the speed at which the system reaches equilibrium in the long run, is negative and significant. ECT is the coefficient that indicates how fast the variables in the model adjust to the long-run equilibrium. A negative sign of ECT represents the convergence in long-run equilibrium. The ECT term magnitude implies that the system returns to long-run equilibrium after a shock in approximately 4.2 years (50 months) with an annual correction of 23.7%.

The long-run coefficients in the model are statistically significant and have the theoretically expected signs. The findings showed that a positive and negative shift in NRE supply contributes to increased carbon emission and consequently reduces environmental quality. In contrast, however, a positive and negative shift in RE supply reduces carbon emissions and hence strengthens environmental quality. This finding points to the asymmetry between the two main components of energy supply and carbon emissions. According to the long-run estimates, a positive shock in RE induces a positive and statistically significant effect of 0.0539 on carbon emissions. A negative shock of RE causes a negative impact of 0.0538 on carbon emissions. The findings demonstrate that a positive shock to RE has a slightly higher impact on carbon emissions. It is clear from the magnitude of the asymmetric coefficients for NRE that its impact on CO_2 is quite high. These findings suggest that the long-run impact of positive shocks in both renewable and non-renewable energy supplies on carbon dioxide emissions is not similar to that of a negative shock, and there are asymmetric effects in the long run.

TABLE 9 Panel ARDL regression with asymmetric effect.

Variables	Model I	Model II	Model III	Model IV	Model V
Long-run Coef					
ln (RE^{+})	−0.204***		0.0128*	−0.00624	−0.0539***
	(0.00984)		(0.00764)	(0.00773)	(0.00484)
ln (RE^{-})	−0.214***		0.00175	−0.0106	−0.0538***
	(0.00987)		(0.00816)	(0.00849)	(0.00489)
ln (NRE^{+})		1.018***	1.025***	1.105***	0.707***
		(0.0182)	(0.0189)	(0.0188)	(0.0319)
ln (NRE^{-})		1.017***	1.023***	1.112***	0.716***
		(0.0178)	(0.0184)	(0.0189)	(0.0324)
ln (GDP)				0.450***	0.967***
				(0.152)	(0.346)
ln $(GDP)^2$				−0.0274***	−0.0581***
				(0.00802)	(0.0181)
ln (POPD)	−1.907*** (0.113)	−0.413*** (0.0357)	−0.538*** (0.0515)		−0.346*** (0.0953)
ec	*−0.195****	*−0.268****	*−0.229****	*−0.262****	*−0.237****
	(0.0328)	*(0.0318)*	*(0.0315)*	*(0.0381)*	*(0.0503)*
Speed of adj. (year)	*5.128*	*3.731*	*4.367*	*3.817*	*4.219*
Short-run Coef					
Δ.ln (RE^{+})	0.0213		0.00517	−0.00342	0.00575
	(0.0432)		(0.0261)	(0.0250)	(0.0270)
Δ.ln (RE^{-})	0.0161		0.00163	−0.0120	−0.00354
	(0.0401)		(0.0261)	(0.0254)	(0.0269)
Δ.ln (NRE^{+})		0.570***	0.610***	0.564***	0.673***
		(0.0588)	(0.0548)	(0.0602)	(0.0711)
Δ.ln (NRE^{-})		0.570***	0.609***	0.564***	0.675***
		(0.0594)	(0.0552)	(0.0607)	(0.0715)
Δ.ln (GDP)				0.542	−6.518
				(4.337)	(4.302)
Δ.ln $(GDP)^2$				−0.0212	0.327
				(0.204)	(0.208)
Δ.ln (POPD)	−0.735	−0.641	−0.771		−0.0649
	(0.984)	(0.561)	(0.591)		(0.672)
Constant	1.983*** (0.355)	0.737*** (0.0972)	0.758*** (0.114)	−0.230*** (0.0323)	−0.268*** (0.0509)
Obs	1,102	1,102	1,102	1,062	1,062
id	38	38	38	38	38
t	29	29	29	22	22

(Continued on following page)

TABLE 9 (*Continued*) Panel ARDL regression with asymmetric effect.

Variables	Model I	Model II	Model III	Model IV	Model V
Log likelihood	2063.405	2641.555	2723.857	2707.184	2735.175
EKC	-	-	-	YES	YES
Turning Point (USD)				3637.29$	4085.77$

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

TABLE 10 Testing asymmetries.

Variables	Model I	Model II	Model III	Model IV	Model V
Panel A: Long-run asymmetries					
ln (RE)	1.81		4.81**	1.55	0.00
	[0.1790]		[0.0282]	[0.2132]	[0.9653]
ln (NRE)		0.05	0.08	1.43	4.51**
		[0.8250]	[0.7792]	[0.2310]	[0.0337]
Panel B: Short-run asymmetries					
ln (RE)			0.99	1.54	1.74
			[0.3198]	[0.1867]	[0.1872]
ln (NRE)	0.88	0.03	1.15	0.00	0.58
	[0.3477]	[0.8737]	[0.2840]	[0.9691]	[0.4470]

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

Moreover, carbon emissions positively respond to increases in GDP; a 1% increase in GDP leads to a positive and statistically significant increase in carbon emissions by 0.967 percent.

5 Conclusion and discussions

This study investigates the short- and long-term asymmetries between CO_2 emissions, RE and NRE under positive and negative shocks for the panel data series of 38 OECD countries between 1990 and 2021, as well as the validity of the Environmental Kuznets Hypothesis with panel data econometrics. While many studies in the literature address asymmetric effects and EKC as energy consumption or utilization, the novelty of this study lies in approach the issue in terms of energy supply along with asymmetric effects for RE and NRE.

Negative and positive shocks in RE and NRE energy supply significantly affect CO_2 emissions in the long run. However, only NRE is effective on emissions in the short run. While NRE has a powerful effect on increasing emission, RE's CO_2 emission-reducing impact is limited. Moreover, Wald test results indicate the existence of an asymmetric link between NRE and emissions in the long run. This finding raises questions about the effectiveness of measures taken against environmental degradation, even in OECD countries known for their high environmental awareness. The findings coincide with the findings of Munir (2022) in the NRE subgroups in EU countries regarding positive shocks but differ in terms of negative shocks. Moreover, the findings support the NRE and RE consumption coefficients of Mujtaba et al. (2022b) regarding symmetric and asymmetric effects for the OECD. However, while our results are quite consistent for RE, our study's magnitude of NRE effects is lower.

The coefficient of GDP is 0.967, and the coefficient of the quadratic term is −0.058, and both coefficients are significant at the 1% level. The positive coefficient of the primary term and the negative coefficient of the quadratic term indicate the existence of an inverted U-shaped curve between economic growth and environmental pollution, supporting the validity of the EKC hypothesis for the study period in the OECD countries. The turning point of the Environmental Kuznets Curve is the calculated *per capita* income level of $4085.77. The findings on EKC are consistent with Sun et al. (2020); Fakher and Inglesi-Lotz (2022).

However, according to 2021 data, only 11.2 percent of the total energy supply in OECD countries is comes from renewable sources. This situation indicates the insufficiency of renewable resources in reducing emissions and the need for more technology, R&D and fixed capital investments in this field. Moreover, to reduce emissions and change the composition of the energy supply in favour of renewable resources, economic policies that encourage the use of renewable energy resources instead of traditional ones should be pursued.

Across the OECD, approximately 11.5 per cent of energy is provided from renewable sources. When analysed on a country basis, it is seen that this ratio rises to 88% in countries rich in renewable natural resources (e.g., Iceland). In comparison, it falls to about 2% in countries poor in natural resources (e.g., South Korea and Israel). These countries have the technical know-how and economic infrastructure to afford renewable energy investments. Therefore, the insufficiency of renewable energy supply cannot be explained only by the insufficiency of natural resources. This situation can be explained by similar countries' environmental insensitivity and high dependence on non-renewable resources. The best policy to overcome this dependence may be to identify the renewable energy resources in which the country is relatively superior and to concentrate new energy investments in these areas.

Governments should develop incentives at both macro and micro levels to increase investments in renewable energy products. The government could provide tax exemptions to firms that adopt a certain percentage of renewable energy sources in their production and operation processes. Taxes and restrictions on the trade of renewable energy-intensive products could be lifted to increase the accessibility of these products to the final consumer. In addition, tariffs on carbon-emitting products could be expanded to impose a carbon tax on these products. This would shift production towards renewable energy-based areas. The contribution of transport services to carbon emissions is significant. Policies to encourage public transport should be followed to minimise emissions in this area. At the same time, carbon emissions in transport can be minimised by implementing green and electrical transport systems.

As in any empirical analysis, the study's limits are directly proportional to the data's accuracy and the model's consistency. We restrict the period to a specific year and countries to the OECD to minimise these limitations. We also subject the results to robustness checks (see Tables A1, A2).

It is possible to improve our findings with further studies. Further studies in subgroups and periods will be helpful to confirm these findings. Future studies could also focus on asymmetric effects according to energy supply sources.

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

DŞ, YM, MS, and EU: conceptualization, methodology, validation, writing—original draft preparation, literature review, data curation, supervision, editing, and resources. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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APPENDIX

TABLE A1 Robustness check Driscoll-Kraay standard errors with asymmetric effect.

Variables	Model I	Model II	Model III	Model IV	Model V
ln (RE^+)	−0.153*** (0.0186)		−0.0435*** (0.00739)	−0.0261*** (0.00604)	−0.0280*** (0.00572)
ln (RE^-)	−0.148*** (0.0176)		−0.0481*** (0.00770)	−0.0296*** (0.00650)	−0.0317*** (0.00613)
ln (NRE^+)		1.023*** (0.0263)	0.976*** (0.0237)	0.961*** (0.0298)	0.964*** (0.0291)
ln (NRE^-)		1.027*** (0.0259)	0.983*** (0.0244)	0.968*** (0.0314)	0.973*** (0.0306)
ln (GDP)				0.766*** (0.138)	0.567*** (0.161)
ln $(GDP)^2$				−0.0426*** (0.00687)	−0.0310*** (0.00837)
ln (POPD)	0.201 (0.190)	−0.201*** (0.0281)	−0.128*** (0.0387)		−0.115** (0.0451)
Constant	0.932 (0.814)	1.781*** (0.107)	1.465*** (0.156)	−2.414*** (0.698)	−1.099 (0.857)
Observations	1,140	1,140	1,140	1,100	1,100
id	38	38	38	38	38
Model F	28.51***	618.42***	551.19***	900.38***	612.48***
R^2	0.1811	0.8362	0.8515	0.8376	0.8402

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

TABLE A2 Robustness check AMG regression with asymmetric effect.

Variables	Model I	Model II	Model III	Model IV	Model V
ln (RE^+)	−0.171*** (0.0585)		−0.0178 (0.0316)	−0.0449 (0.0296)	−0.0487 (0.0323)
ln (RE^-)	−0.170*** (0.0564)		−0.0228 (0.0322)	−0.0347 (0.0264)	−0.0438 (0.0323)
ln (NRE^+)		0.882*** (0.0494)	0.887*** (0.0490)	0.804*** (0.0626)	0.826*** (0.0624)
ln (NRE^-)		0.887*** (0.0493)	0.890*** (0.0490)	0.807*** (0.0627)	0.831*** (0.0625)
ln (GDP)				1.559 (4.485)	1.975 (4.650)
ln $(GDP)^2$				−0.0628 (0.214)	−0.0691 (0.225)
ln (POPD)	−1.138* (0.626)	−0.784** (0.387)	−1.016** (0.410)		−0.0167 (0.406)
cdp	0.881*** (0.167)	0.516** (0.257)	0.416** (0.207)	0.803*** (0.243)	0.766*** (0.206)
trend	0.0101* (0.00565)	−0.00146 (0.00389)	−0.000535 (0.00420)	0.00296 (0.00342)	−0.00284 (0.00466)
Constant	6.367** (2.737)	4.136** (1.711)	4.875*** (1.881)	−8.259 (23.52)	−11.58 (23.96)
Observations	1,140	1,140	1,140	1,100	1,100
id	38	38	38	38	38
Model Wald	12.16***	336.81***	421.13***	371.13***	428.59***
RMSE	0.0537	0.0274	0.0246	0.0204	0.0189

Standard errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Variable "cdp" refers to the common dynamic process. Variable "trend" refers to the group-specific linear trend terms.