ECONOMIC ANNALS, Volume LXX, No. 244 / January – March 2025
UDC: 3.33 ISSN: 0013-3264

https://doi.org/10.2298/EKA2544007B

Abdulkadir Bulut[*]
Nazmiye Tekdemir[**]

THE INVERTED N-SHAPED RELATIONSHIP BETWEEN ECONOMIC GROWTH AND CO_2 EMISSIONS: EVIDENCE FROM OECD COUNTRIES

ABSTRACT: *Modern economic growth has led to increased levels of international trade, large-scale industrialisation, and major technological advancements, resulting in substantial negative externalities on a global scale. Among these, environmental degradation has emerged as a significant global public bad. Balancing economic growth objectives while addressing environmental challenges remains a critical issue for modern society. This study examines the relationship between economic growth and environmental degradation across 33 OECD countries during the period 1996-2015, employing a fixed effects model with the Driscoll-Kraay standard error estimation approach. The analysis reveals an inverted N-shaped relationship between economic growth and* CO_2 *emissions, contradicting the conventional environmental Kuznets curve theory. The results also show that renewable energy consumption and stronger institutional quality help reduce* CO_2 *emissions, while non-renewable energy consumption and higher levels of industrial activity have the opposite effect.*

KEY WORDS: *environmental quality, global public bad, EKC hypothesis, renewable energy, institutional quality*

JEL CLASSIFICATION: Q56, D62, H41, Q20

---

[*] Faculty of Economics and Administrative Sciences, Hitit University, Corum, Turkiye, e-mail: kadirbulut0710@gmail.com (corresponding author), ORCID: 0000-0001-6351-0583

[**] Faculty of Economics and Administrative Sciences, Kirikkale University, Kirikkale, Turkiye, e-mail: nazmiyekirik@gmail.com, ORCID: 0000-0002-7292-569X

1. INTRODUCTION

Environmental degradation has emerged as one of the most pressing global public harms, a concept that has gained increasing acceptance in public finance since Kaul et al. (1999) introduced the global public goods doctrine within the United Nations Development Programme. Unlike other challenges, the negative externalities of environmental damages such as climate change, deforestation and pollution transcend national borders and extend across borders and generations. The widespread and long-lasting effects of environmental degradation require interventions at the national and international levels and make the study of its relationship with economic growth vital for developing effective policies aimed at ensuring sustainable development.

Since the Industrial Revolution, human-caused releases of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have become major drivers of global warming, making them central targets in international efforts to combat climate change (Jones et al., 2023). This has led to a strong focus on tracking each country's role in climate change as well as setting fair reduction goals (de-carbonisation commitments) for all nations. Global warming, as predicted by most climate models, is expected to persist in the near future (2021–2040), reaching 1.5°C even under the lowest greenhouse gases (GHG) emission scenario and this persistence is primarily driven by heightened cumulative CO_2 emissions (Intergovernmental Panel on Climate Change (IPCC) (2023). The urgency of the situation is underscored by recent data. The latest IPCC report (2023) reveals that atmospheric CO_2 concentrations reached record highs (410 parts per million) in 2019, the highest level in at least 2 million years. This highlights the necessity for more decisive actions to reduce fossil fuel consumption.

While certain international efforts focus on reducing emissions, a key challenge remains achieving sustainable economic development without compromising environmental well-being. Achieving this equilibrium requires a comprehensive understanding of the complex relationship between economic development and environmental destruction.

The environmental Kuznets curve (EKC) hypothesis, building on the inverted U-shaped relationship between income inequality and economic growth identified by Simon Kuznets (1955), is one of the main conceptualisations dealing with the relationship between the environment and the economy. It suggests that as economies grow, environmental destruction initially worsens, but this trend reverses at higher development levels. Grossman and Krueger (1991)[1], pioneers in studying the relationship between environmental pollution and economic growth, suggest that while various pollutants such as sulphur dioxide, dark matter and suspended particles increase with GDP per capita at lower national income levels, environmental pollution decreases at higher income levels. Since Grossman and Krueger's seminal work, numerous studies have focused on validating the EKC hypothesis, primarily investigating its applicability to the relationship between carbon emissions and income[2].

As previously noted, most EKC studies aim to confirm the inverted U-shape pattern. However, a subset of studies, inspired by works such as those by Grossman and Krueger (1995), Panayotou (1997), Dinda (2004), Galeotti et al. (2006), and Akbostancı et al. (2009), have incorporated a cubic term into their models. This term allows researchers to investigate the possibility of a reversal in the trend, where environmental degradation might increase again at very high-income levels, (Özokcu & Özdemir, 2017). The research on (inverse) N-shaped EKC hypothesis remains limited, especially for OECD countries (Özokcu & Özdemir 2017; Ullah et al., 2024).

The present study investigates the EKC hypothesis for 33 OECD countries from 1996 to 2015, analysing the impact of economic growth on CO_2 emissions while considering the role of renewable and non-renewable energy consumption. Notably, it departs from prior studies by incorporating a cubic term in the analysis to examine the potential for an (inverted) N-shaped relationship. Intriguingly, our findings challenge the conventional EKC theory by revealing an inverted N-shaped relationship between economic growth and air pollution levels. The implications of this inverted N-shaped relationship are profound, signalling that unchecked economic growth might not lead to automatic environmental improvement, even though growth may ultimately appear to

---

[1] It is important to note that Grossman and Krueger (1991) did not analyse CO_2 emissions in their study due to data limitations at the time. However, many studies mistakenly assume that the authors include CO_2 as a measure of environmental degradation in their analyses.

[2] For a thorough examination, refer to the research paper "What have we learned from Environmental Kuznets Curve hypothesis? A citation-based systematic literature review and content analysis." by Naveed et al. (2022).

improve the environment. Therefore, this study highlights the need for targeted and effective environmental policies to mitigate the adverse environmental impacts of economic development. Policymakers must recognise the complexities in addressing the challenges posed by varying levels of environmental degradation across different income brackets. Furthermore, testing this hypothesis and modelling the relationship between the environment and economic growth with OECD countries will be very instructive considering the distribution of economic power in the world economy. As a matter of fact, OECD countries, in addition to their economic power, may play a leading role in reaching effective solutions on a global scale with their advantages of international cooperation.

OECD countries prioritise transitioning to renewable energy sources as a key strategy to combat global environmental issues such as climate change, air and water pollution, and biodiversity loss. To assess the significance of this transition, this study utilises renewable and non-renewable energy consumption as control variables. We further included the "Rule of Law" (RL) indicator from the World Governance Indicators (WGI) as a proxy for institutional strength in environmental regulation. This addition is grounded in the understanding that institutions play a critical role in enforcing environmental laws, developing regulatory frameworks, and ensuring compliance, which can significantly affect environmental outcomes at different stages of economic growth (Dinda, 2004; Karim et al., 2022; Panayotou, 1997). Industrialisation is also controlled for, given that structural economic changes can significantly impact environmental outcomes, with higher industrial activity generally associated with increased environmental pressures (Li & Lin, 2015). Lastly, we conducted estimations for two distinct dependent variables, namely total GHG emissions and CO_2 emissions, to validate the robustness of the study's findings.

The remainder of the paper proceeds as follows. Section 2 highlights the relevant literature on the EKC for OECD countries. Section 3 details the data utilised, outlining sources and variables. Section 4 explains the chosen model and methodology, including the rationale and analytical techniques. Section 5 presents the key findings from the data analysis. Finally, Section 6 addresses the conclusions drawn from the study and explores potential policy implications.

2. SELECTED EMPIRICAL LITERATURE

The EKC hypothesis is a popular concept tested by researchers. It suggests an inverted U-shaped relationship between economic growth and environmental degradation. Economic growth is first thought to increase pollution, but after reaching a certain income level, societies prioritise environment at higher income levels, leading to a decline in pollution. In other words, once the economy has accumulated sufficient capital stock, it is possible to restore environmental quality. In essence, the EKC hypothesis argues that economic growth may eventually become a solution, not just a cause, of environmental pollution; therefore, policies that promote economic growth should not be sacrificed in the quest to reduce pollution (Dinda, 2004). However, critics argue that the EKC hypothesis is highly optimistic. They argue that there is no guarantee economic growth will give rise to environmental improvement, and it might even exacerbate ecological issues (Arrow et al., 1995; Beckerman, 1995).

Building on Grossman and Krueger's (1991) work, researchers have estimated the EKC using different methodologies across various contexts (Ahmed & Long, 2012; Aldy, 2005; Apergis & Payne, 2010; Bölük & Mert, 2015; Cole et al., 1997; Doğan & Şeker, 2016; Galeotti & Lanza, 1999; Galeotti et al., 2006; Gill et al., 2018; Hill & Magnani, 2002; Holtz-Eakin & Selden, 1995; Jalil & Mahmud, 2009; Magnani, 2001; Nasreen et al., 2017; Öztürk & Acaravcı, 2013; Panayotou, 1993; Shahbaz et al,. 2013; Sinha & Sen, 2016; Tamazian & Rao, 2010; Vollebergh et al., 2005; Yavuz, 2014). However, these studies lack consensus on the EKC's shape due to differences in model definitions, the choice of explanatory variables, timeframes, and geographical scope. The outcomes of these investigations indicate a linearly increasing or decreasing relationship, as well as a U-shaped or inverted U-shaped pattern supporting the EKC hypothesis.

Extending the work of Grossman and Krueger (1995), some studies challenge the EKC by analysing economic growth in a cubic form, suggesting an N-shaped or inverted N-shaped relationship. The N-shaped relationship indicates that the decrease in environmental degradation with economic growth is a temporary phenomenon (Akbostancı et al., 2009; Day & Grafton, 2003; Fodha & Zaghdoud, 2010; Fosten et al., 2012; He & Richard, 2010; Hill & Magnani, 2002; Lorente & Álvarez-Herranz, 2016; Moomaw & Unruh, 1997). Meanwhile, the inverted N-shape suggests that pollution initially falls but rises again with further income growth, eventually declining after a high-income threshold (Abbasi et al., 2023; Abdallah et al., 2013; Dijkgraaf & Vollebergh, 2005; Dong et al., 2016; Fakher et al., 2023; Farooq et al., 2024; Huang et al., 2023; Nasr et al., 2015; Vollebergh et al., 2005; Yaduma et al., 2015).

In this study, we examine the (inverted) N-shaped EKC hypothesis within the context of OECD countries. We, therefore, present the findings from several selected studies focusing on OECD nations in the literature. Georgiev and Mihaylov (2015) investigated the validity of the EKC hypothesis across 30 OECD countries using four local air pollutants, sulphur oxides (SOx), nitrogen oxides (NOx), carbon monoxide (CO), and volatile organic compounds (VOC), with two global pollutants (CO_2, GHG) as dependent variables. The findings varied depending on the dependent variables. Specifically, the curve for the CO_2 and GHG emissions exhibited a linear increase. In contrast, the SOx emissions yielded a U-shaped curve, while employing the CO, VOC, and NOx variables resulted in an inverted U-shape.

Jebli et al. (2016) utilised both the FMOLS and DOLS methods across 25 OECD countries spanning the years 1980 to 2010. They confirmed the presence of an inverted U-shaped EKC within the data from the sample. In contrast, Özokcu and Özdemir (2017) analysed 26 high-income OECD countries for the years between 1980 and 2010 and found evidence against the EKC hypothesis. Their results suggest an inverted N-shaped curve, implying economic growth may not inherently decrease environmental damage.

Churchill et al. (2018) examined the EKC hypothesis for 20 OECD countries from 1870 to 2014. Their country-level analyses revealed diverse outcomes. While five countries (Finland, France, Spain, the UK, and the USA) exhibit an inverted U-shaped relationship, consistent with the EKC hypothesis, three countries (Australia, Canada, and Japan) show an N-shaped curve, and one (Denmark) reveals an inverted N-shaped curve. Notably, in 11 countries, no significant relationship was found between economic growth and environmental pollution.

Lau et al. (2019), using panel GMM and FMOLS methods for 18 OECD countries, questioned the validity of the EKC hypothesis on the basis of nuclear energy data for the period 1996–2015. That is, in their study, the effects of electricity generation from nuclear sources, electricity generation from non-renewable sources and trade openness on CO_2 emissions were investigated. Their results point to an inverted U curve and support the idea that electricity generated from nuclear sources leads to lower CO_2 emissions without delaying long-term growth in these countries. Ng et al. (2019) used the PMG, panel FMOLS, and panel DOLS approaches for 25 OECD countries. Their results support an inverted U-shaped relationship.

Leal and Marques (2020) examined the EKC hypothesis for the 20 highest CO_2-emitting OECD countries (1990–2016) by analysing different dimensions of globalisation. They divided the countries into low- and high-globalisation groups based on rankings. Their findings supported the EKC hypothesis only in highly globalised countries, suggesting that economic growth might improve environmental quality in more integrated economies. Conversely, the EKC did not hold for low-globalisation OECD countries. This study highlights the importance of considering different aspects of globalisation when examining its link to environmental pollution.

The study by Isik et al. (2021) investigated the EKC hypothesis for 8 OECD countries utilising Driscoll-Kraay standard errors and the CCEMG estimator for robust analysis. They tested the EKC hypothesis using a different method. This method involved decomposing the per capita GDP series into periods of increase and decrease, focusing only on the economic growth phases in the model. They argued that this approach better reflects the core idea of the EKC hypothesis. The standard model, using undecomposed GDP data, supported the EKC hypothesis for four countries (Türkiye, Australia, Canada, and France). However, when they applied their method with decomposed GDP data, the EKC hypothesis was not supported in any country.

Our study addresses a critical gap by investigating the validity of the inverted N-shaped EKC in OECD countries. While prior research has extensively examined the EKC hypothesis, limited studies have focused on OECD nations, particularly regarding the differential impacts of renewable and non-renewable energy consumption. Additionally, we employ two distinct environmental degradation measures to strengthen the robustness of our analysis. This study aims to contribute to a deeper understanding of the complex relationship between the environment and economic development in OECD nations, offering valuable insights for policymakers navigating the energy transition.

3. DATA

This study applies a set of panel data for the 33 OECD countries covering the period spanning from 1996 to 2015[3]. All the data in this study were extracted from the World Development Indicators (WDI)[4]. Detailed information about the data used in the study is given in Table 1.

Table 1: Variable descriptions

Acronyms	Variables	Measurement Units	Source
Dependent variables			
LNCO$_2$	CO$_2$ emissions	Metric tons per capita	The World Bank, 2024
LNGH	Total greenhouse gas emissions	kt of CO$_2$ equivalent	The World Bank, 2024
Explanatory variable			
LNGDP	GDP per capita	Constant 2017 international $	The World Bank, 2024
Control variables			
REN	Renewable energy consumption	% of total final energy consumption	The World Bank, 2024
NREN	Fossil fuel energy consumption	% of total	The World Bank, 2024
LNRL	Rule of Law	Percentile ranks	The WGI, 2024
IND	Industry	Industry (including construction), value added (% of GDP)	The World Bank, 2024

---

[3] Advanced Economies: Australia, Austria, Belgium, Canada, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Iceland, Ireland, Israel, Italy, Japan, the Republic of Korea, the Netherlands, New Zealand, Norway, Portugal, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, the United Kingdom, United States.
Emerging Economies: Chile, Hungary, Mexico, Poland, Türkiye.

[4] https://datatopics.worldbank.org/world-development-indicators/

$LNCO_2$ is the logarithm of per capita carbon dioxide emissions. Carbon dioxide emissions include carbon dioxide produced during the consumption of solid, liquid, and gaseous fuels and during gas flaring. LNGH shows the logarithm of total GHG emissions. Total GHG emissions refer to a sum in carbon dioxide equivalent, including anthropogenic sources of methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (HFCs, PFCs, and SF_6), which exclude short-cycle biomass burning activities but include other sources of biomass combustion (e.g., forest fires, post-combustion decay, peat fires, and the decay of drained peatlands). LNGDP refers to the logarithmic transformation of GDP per capita, serving as a measure of income level. REN is the share of renewable energy obtained from natural resources such as solar, wind, hydroelectric, biomass, and geothermal in the total final energy consumption. NREN denotes fossil fuel energy consumption as a non-renewable energy source. It is the total energy consumption of a country as a percentage of the amount of energy obtained from fossil fuels such as coal, oil, and natural gas. To incorporate the role of institutional capacity in shaping environmental outcomes, we include the LNRL variable which is the logarithm of "Rule of Law" from the WGI. This measure reflects the extent to which individuals and institutions in a country adhere to established societal rules, encompassing elements such as the effectiveness of contract enforcement, protection of property rights, reliability of law enforcement agencies, and the functioning of judicial systems. The LNRL is measured as percentile ranks, with values ranging from 0 to 100, with higher ranks indicating stronger institutional quality. We include the variable Industry (IND), value added (% of GDP) from the World Bank, to account for the impact of structural economic changes on environmental outcomes. This variable captures the extent to which a country's GDP is derived from industrial activities, including manufacturing and construction.

4. MODEL AND METHODOLOGY

Our baseline model is specified as follow:

$$E=f\,(Y, Y^2, Y^3, Z) \tag{1}$$

where E represents each of the environmental damage indicators, Y denotes income, Y^2 denotes income squared, Y^3 denotes income cubed, and Z includes other explanatory variables that may influence environmental degradation. The empirical model assumes the following structure:

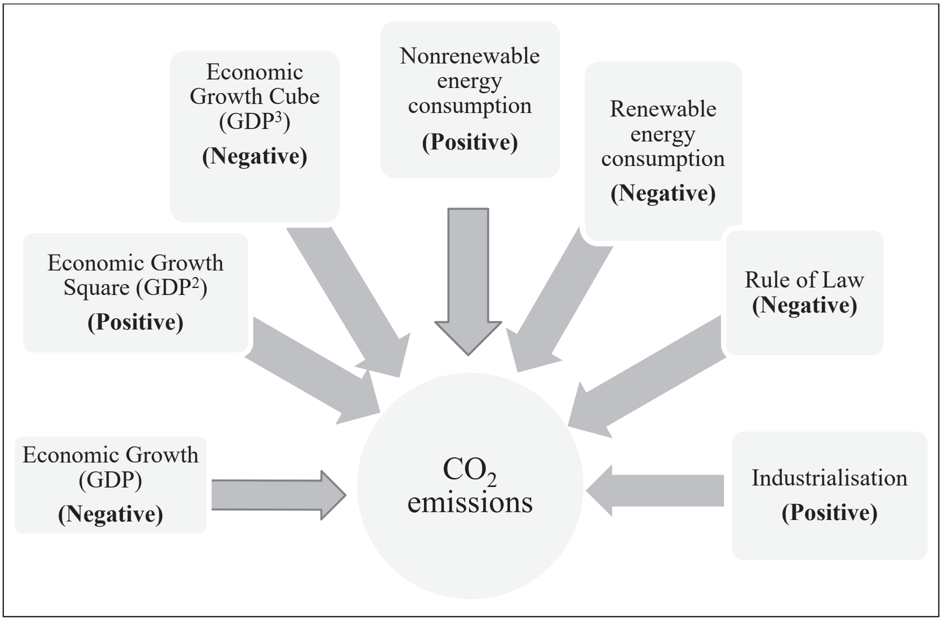
$$LNCO_{2_{it}} = \beta_0 + \beta_1 LNGDP_{it} + \beta_2 LNGDP_{it}^2 + \beta_3 LNGDP_{it}^3 + \beta_4 REN_{it} + \beta_5 NREN_{it} + \beta_6 LNRL_{it} + \beta_7 IND_{it} + \mu_{it} + \eta_t + \varepsilon_{it} \,, \tag{2}$$

where i is the cross-sectional country index and t is the time index. $LNGDP$, $LNGDP^2$, and $LNGDP^3$ represent the log transformed per capita real GDP in linear, quadratic, and cubic form, respectively. REN is renewable energy consumption (% of total) and $NREN$ is non-renewable energy consumption (% of total), $LNRL$ is the logarithm of "Rule of Law" measured as percentile ranks, and IND is industry (% of GDP). Finally, μ captures state-specific effects, η represents time-specific effects, and ε is the error term. The sign of coefficient β related to income, determines the specific shape of the EKC:

- $\beta_1 = \beta_2 = \beta_3 = 0$: There is no association between income growth and pollution levels. Changes in income have no impact on pollution in this scenario.
- $\beta_1 > 0, \beta_2 = \beta_3 = 0$: Pollution increases linearly with income growth. As income rises, pollution is expected to proportionally increase.
- $\beta_1 < 0, \beta_2 = \beta_3 = 0$: Pollution decreases linearly with income level. This suggests that stricter environmental regulations or technological advancements might be offsetting the negative impact of income growth on pollution.
- $\beta_1 > 0, \beta_2 < 0, \beta_3 = 0$: This represents the inverted U-shaped EKC. Initially, pollution increases with income growth ($\beta_1 > 0$). However, as income continues to rise ($\beta_2 < 0$), pollution starts to decrease.
- $\beta_1 < 0, \beta_2 > 0, \beta_3 = 0$: This represents a U-shaped EKC. Initially, pollution might decrease with income growth ($\beta_1 < 0$) due to initial environmental improvements. However, as income continues to rise ($\beta_2 > 0$), pollution might begin to rise again, potentially due to the unsustainable practices or limitations of initial improvements.
- $\beta_1 > 0, \beta_2 < 0, \beta_3 > 0$: This describes an N-shaped EKC. Similar to the inverted U-shape, pollution rises with income initially ($\beta_1 > 0$). However, the decline in pollution ($\beta_2 < 0$) is followed by another increase ($\beta_3 > 0$) at even higher income levels. This could stem from factors like increased consumption patterns or limitations of previous pollution control strategies.

- $\beta_1 < 0, \beta_2 > 0, \beta_3 < 0$: This represents an inverted N-shaped EKC. Here, this indicates an initial increase in pollution ($\beta_1 < 0$) with economic growth, followed by a decline ($\beta_2 > 0$) as income reaches a certain level, eventually leading to lower pollution at higher income levels ($\beta_3 < 0$). This pattern is a less common scenario, but it may potentially reflect specific policy changes or technological advancements at various development stages. The study summarises the theoretical framework of the inverted-N shaped relationship among the variables in Figure 1.

Figure 1. Theoretical framework of the study



5. EMPIRICAL RESULTS AND DISCUSSION

Table 2 presents the summary statistics for the chosen variables, while Table 3 depicts the correlation between the independent and dependent variables. Notably, $LNCO_2$ is positively and significantly correlated with LNGDP and NREN, suggesting a link between economic growth, non-renewable energy use, and emissions. In contrast, REN and LNRL are significantly negatively correlated with CO_2 emissions, indicating potential environmental benefits from renewable energy and stronger institutional frameworks. IND does not show a significant correlation with CO_2 emissions, highlighting potential structural variability in emission patterns.

Table 2: Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
$LNCO_2$	660	2.083	0.406	1.112	3.019
LNGH	660	11.945	1.452	8.017	15.734
LNGDP	660	10.473	0.378	9.484	11.18
REN	660	0.168	0.155	0.006	0.778
NREN	660	0.739	0.199	0.103	0.985
LNRL	660	4.421	0.214	3.301	4.605
IND	658	0.26	0.049	0.141	0.408

Table 2: Matrix of correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) $LNCO_2$	1.000						
(2) LNGH	0.282	1.000					
	(0.000)						
(3) LNGDP	0.424	0.036	1.000				
	(0.000)	(0.352)					
(4) REN	-0.242	-0.603	0.220	1.000			
	(0.000)	(0.000)	(0.000)				
(5) NREN	0.138	0.595	-0.189	-0.736	1.000		
	(0.000)	(0.000)	(0.000)	(0.000)			
(6) LNRL	0.446	-0.142	0.722	0.272	-0.287	1.000	
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)		
(7) IND	-0.043	-0.003	-0.304	0.046	0.055	-0.259	1.000
	(0.268)	(0.931)	(0.000)	(0.237)	(0.161)	(0.000)	

To assess the presence of cross-sectional dependence (CSD) in our data, we employ the Pesaran (2004) test. Table 4 reports the results, where the null hypothesis of no CSD is rejected for all variables at a 1% significance level, except LNRL. This confirms the existence of cross-sectional dependence within the data series for the variables. The stationarity properties of the variables are examined using Pesaran's Cross-sectionally Augmented Dickey-Fuller (CADF) test due to the presence of cross-sectional dependence. Table 5 reveals that all variables achieve stationarity only in their first-differenced form (i.e., they are integrated of order one I(1)).

Table 4: Pesaran (2004) cross-section dependence test

Variable	CD-test	p-value
$LNCO_2$	32.607*	0.000
LNGH	14.830*	0.000
LNGDP	86.719*	0.000
REN	42.164*	0.000
NREN	39.403*	0.000
LNRL	-1.034	0.301
IND	42.099*	0.000

*, **, and *** denote significance at the 1%, 5%, and 10% levels, respectively.

Table 5: Cross-sectionally dependent panel unit root test

Variable	Level		First difference	
	t-bar	p-value	t-bar	p-value
$LNCO_2$	-1.579	0.803	-3.323*	0.000
LNGH	-1.234	0.997	-3.310*	0.000
LNGDP	-1.884	0.193	-2.295*	0.001
REN	-1.457	0.938	-2.997*	0.000
NREN	-1.585	0.794	-3.234*	0.000
LNRL	-2.823	0.509	-2.823*	0.000
IND	-0.322	0.374	-4.901*	0.000

*, **, and *** denote significance at the 1%, 5%, and 10% levels, respectively.

Additionally, the study conducted post-fixed effects estimations, including Wooldridge tests for assessing serial correlation among the estimated parameters, and a modified Wald statistic to detect group-wise heteroscedasticity within the residuals of fixed effect regressions. The outcomes of these tests, displayed in

Table 6, reveal the presence of both heteroscedasticity and autocorrelation within the dataset under examination in this study.

Table 6: Heteroscedasticity and autocorrelation tests

Modified Wald test for groupwise heteroscedasticity	Chi-square	p-value
	3262.73	0.0000
Wooldridge test for autocorrelation	F-test	p-value
	96.478	0.0000

Given the identified issues of cross-sectional dependence, heteroscedasticity, and autocorrelation within the dataset, it is imperative to use appropriate statistical techniques to address these challenges and ensure the validity of the study's findings. In this regard, the utilisation of Driscoll-Kraay standard errors presents a compelling solution (Hoechle, 2007).

Table 7 illustrates the regression results of Driscoll-Kraay standard errors with the fixed effects (FE) and random effects (RE) model. We employed the Hausman test before calculating Driscoll and Kraay standard errors and reported Chi-square probability at the bottom of the table. The Hausman test with a probability value of 0.0001 suggests significant bias in the random effects model. Therefore, we prefer the fixed effects model for more consistent estimates.

Regarding Driscoll-Kraay standard errors with the FE model result, all variables show statistical significance at the 1% level. The estimated coefficients for LNGDP, $LNGDP^2$, and $LNGDP^3$ are -114.399, 11.220, and -0.365, respectively, providing empirical support for the hypothesis of an inverted N-shaped EKC in the OECD sample of 33 countries. More specifically, pollution falls with economic development at the early stages. However, beyond a certain threshold of economic development, further increases in GDP per capita results in increased CO_2 emissions, reflecting the environmental costs associated with industrialisation and rising energy demands (the scale effect). Eventually, at even more advanced stages of development, further economic growth correlates with a subsequent decline in pollution. This may be due to factors such as technological advancements, shifts towards cleaner energy sources (the technology effect), heightened environmental awareness and the implementation of environmental policies and regulations. Our findings support the earlier results of Özokcu and Özdemir (2017) but contradict the findings of Ullah et al. (2024), who reported an N-shaped curve for 17 OECD countries, and other studies finding an inverted U-shape for OECD countries (Churchill et al., 2018; Jebli et al., 2016; Lau et al., 2019).

Sinha et al. (2018) argue that simply looking at the signs of the coefficients without verifying the first and second order conditions of the mathematical model employed is not sufficient to confirm an (inverted) N-shaped EKC. Instead, two conditions must be met: (i) $\beta_1, \beta_3 < 0, \beta_2 > 0$, and (ii) $\beta_2^2 - 3\,\beta_1\,\beta_3 > 0$ (Sinha et al., 2018). The first condition ensures the downward and upward slopes of the curve, while the second condition guarantees the existence of real turning points. By applying these conditions and testing our model mathematically, we verify the validity of the inverted N-shaped EKC finding in the dataset of 33 OECD countries[5].

The results reveal a negative and significant correlation between REN and carbon emissions. Specifically, a 1% increase in REN usage corresponds to a reduction in environmental degradation of 1.773% in OECD countries. This suggests that incorporating renewable energy sources helps mitigate emission levels, offering a valuable means to alleviate the ecological impact of human activities. This finding is further supported by the study of Destek and Sinha (2020) on OECD nations. Given these findings, it is advisable for OECD governments to actively promote greater adoption of renewable energy. Strategies may include increasing investment in the renewable energy sector and implementing measures to lower the cost of renewable energy, thereby stimulating demand. By undertaking such initiatives, governments can foster a more sustainable energy landscape while concurrently addressing environmental concerns. A 1% increase in NREN consumption is associated with a statistically significant 0.47% rise in CO_2 emissions, supporting findings in the existing literature that identify NREN use as a major contributor to emissions.

---

[5] $\beta_2^2 - 3\beta_1\beta_3 = (11.220)^2 - 3(-114.399)(-0.365) = 0.621$
Since 0.621> 0, the second condition is also satisfied.

Furthermore, our analysis emphasises the importance of strong institutions in addressing environmental challenges. The findings reveal that the RL variable has a significant negative effect on environmental outcomes. Our findings are in line with recent studies emphasising the impact of institutional quality on the environment (Apergis & Ozturk, 2015; Leal & Marques, 2022; Salman et al., 2019; Wang et al., 2024). Therefore, countries with higher institutional effectiveness are generally better positioned to manage the environmental impacts of economic growth, leading to a pattern where pollution levels eventually decrease. Finally, the results show that higher levels of industrial activity are associated with increased CO_2 emissions, highlighting the environmental impact of industrialisation. This finding is also consistent with studies such as Lin et al. (2015), Zafar et al. (2020) and Nasir et al. (2021), which point to the correlation between industrialisation and carbon emissions.

Table 7: Estimation results of FE and RE with the Driscoll-Kraay standard error approach

DV: $LNCO_2$	DK-FE				DK-RE		
	Coef.	Std.Err.	Prob.		Coef.	Std.Err.	Prob.
LNGDP	-114.399*	20.233	0.000		-112.729*	17.153	0.000
LNGDP2	11.220*	1.964	0.000		11.051*	1.675	0.000
LNGDP3	-0.365*	0.064	0.000		-0.359*	0.055	0.000
REN	-1.773*	0.102	0.000		-1.714*	0.195	0.000
NREN	0.474*	0.072	0.000		0.419*	0.084	0.000
LNRL	-0.158**	0.055	0.010		-0.121**	0.060	0.058
IND	0.500**	0.230	0.042		0.476	0.300	0.128
_cons	389.514*	69.422	0.000		383.831*	58.725	0.000
Observations	658				658		
N	33				33		
Prob> Chi2	0.0001						

*, **, and *** denote significance at the 1%, 5%, and 10% levels, respectively.

To verify the reliability of our results, we used total GHG emissions as the dependent variable. The analysis details are presented in Table 8.

Table 3: Robustness check

DV: LNGH	DK-FE				DK-RE		
	Coef.	Std.Err.	Prob.		Coef.	Std.Err.	Prob.
LNGDP	-80.881*	24.617	0.004		-82.352*	21.661	0.001
LNGDP2	7.866*	2.394	0.004		8.008*	2.099	0.001
LNGDP3	-0.254*	0.078	0.004		-0.258*	0.067	0.001
REN	-2.043*	0.144	0.000		-2.050*	0.099	0.000
NREN	0.228*	0.056	0.001		0.255**	0.112	0.034
LNRL	-0.193**	0.076	0.021		-0.199**	0.072	0.013
IND	0.354	0.209	0.107		0.351	0.224	0.134
_cons	288.412*	84.205	0.003		293.473*	74.274	0.001
Observations	658				658		
N	33				33		
Prob> Chi2	0.0011						

*, **, and *** denote significance at the 1%, 5%, and 10% levels, respectively.

Conducting the Hausman test prior to estimations, we find a *p*-value of 0.001, indicating preference for the fixed effects model. Notably, all coefficients remain significant at the 1% level and reinforce the presence of the inverted N-shaped pattern that characterises the relationship between economic development and emissions in OECD countries. Additionally, the signs of the coefficients for the control variables remain consistent with the main analysis. Reinforcing the robustness of our findings, the mathematical conditions for an inverted N-shaped EKC ($ß_1 < 0$, $ß_3 < 0$, $ß_2 > 0$, and $ß_2^2 - 3ß_1ß_3 > 0$) are again satisfied in the robustness check using total GHG emissions as the dependent variable.

We further divided the sample into advanced (28 countries) and emerging economies (5 countries), given the diverse nature of OECD countries in terms of income levels based on the IMF classification (Appendix Table A1, A2, A3, and A4). This division addresses the heterogeneity among OECD nations, as countries with higher income levels and more developed infrastructure may exhibit different environmental patterns than emerging economies. Our findings indicate that the inverted N-shaped EKC pattern holds for advanced economies, whereas this pattern does not emerge for emerging countries. Additional analyses using LNGH as the dependent variable yielded consistent results, further supporting the robustness of the inverted N-shaped EKC pattern for advanced economies. This suggests that our original findings primarily reflect the advanced OECD nations. However, we acknowledge that the smaller sample size of emerging economies (only five nations) may limit the statistical power and generalisability of the results for this subgroup.

6. CONCLUSION

Environmental destruction has been of great interest to researchers and policymakers and has taken a central place on their agendas. Decades of research have studied the complex interplay of factors underlying global environmental problems. However, the quests for comprehensive solutions are still on-going. Especially with the continuous increase in industrial production, increasing gas emissions have led to a cross-border externality, leading to such critical problems as ozone depletion and climate change.

Escalating environmental concerns highlight the need for a deeper understanding of economic growth patterns in advanced economies, particularly OECD countries, whose dominance in the international arena grants them significant influence over environmental outcomes. This paper investigates the impact of economic growth on the environment within the framework of the EKC hypothesis, considering the role of both renewable and non-renewable energy consumption. Specifically, we aim to empirically validate the (inverted) N-shaped EKC hypothesis in 33 OECD economies using panel data analysis from 1996 to 2015.

The analysis yielded surprising findings that challenge the conventional EKC theory. According to the regression results, the income (GDP), the income squared (GDP^2), and the income cubed (GDP^3) have a negative, positive, and negative impact on environmental destruction, respectively. In other words, the findings reveal an inverted N-shaped EKC curve, signalling that unchecked economic growth might not lead to automatic environmental improvement, even though growth may appear to improve the environment in the long run. We also find that incorporating renewable energy sources plays a vital role in mitigating emissions, offering a valuable means to alleviate the environmental pressures of human activities.

Overall, environmental problems represent a critical global threat that transcends national borders, generating negative externalities impacting both current and future generations. These multifaceted issues demand a comprehensive approach. Yet, global environmental challenges are the result of contributions from numerous countries, and no single nation acting alone can effectively resolve them. Therefore, combating environmental problems necessitates international cooperation and coordination, alongside strong institutions and well-designed national public policies. Furthermore, a shift towards cleaner energy alternatives, for example renewable sources such as solar and wind power, is crucial to achieve sustainable economic development. Further studies could investigate the effectiveness of specific environmental policies in different contexts to provide evidence-based guidance for policymakers.

While this study offers insights into the relationship between economic growth and environmental degradation in OECD countries, it has some limitations. First, focusing solely on OECD countries may limit the generalisability to non-OECD nations with different economic structures and policies. Future research could be expanded to include a more diverse set of countries to better capture global EKC dynamics. Second, the 1996–2015 timeframe, although capturing important changes, may not reflect recent policies and technologies. Extending this period as well as examining additional environmental indicators such as the ecological footprint or load capacity factor could test the persistence of the inverted N-shaped EKC across varied forms of degradation. Third, while our model controls for energy consumption, industrialisation, and institutional quality, such factors as trade openness, urbanisation, and innovation may also play roles. Including these could provide a more complete view of EKC influences. Lastly, although we address cross-sectional dependence and autocorrelation with DK standard errors, future studies might consider dynamic panel data models or instrumental variable approaches to further account for endogeneity. In summary, expanding the sample, updating the period, broadening environmental indicators and controls, and exploring advanced methods are valuable next steps to enhance our understanding of the EKC.

REFERENCES

Abbasi, K. R., Awan, A., Bandyopadhyay, A., Rej, S., & Banday, T. P. (2023). Investigating the inverted N-shape EKC in the presence of renewable and nuclear energy in a global sample. *Clean Technologies and Environmental Policy*, *25*(4), 1179–1194.

Abdallah, K. B., Belloumi, M., & De Wolf, D. (2013). Indicators for sustainable energy development: A multivariate cointegration and causality analysis from Tunisian road transport sector. *Renewable and Sustainable Energy Reviews*, *25*, 34–43.

Ahmed, K., & Long, W. (2012). Environmental Kuznets curve and Pakistan: An empirical analysis. *Procedia Economics and Finance*, *1*, 4–13.

Akbostancı, E., Türüt-Aşık, S., & Tunç, G. İ. (2009). The relationship between income and environment in Turkey: Is there an environmental Kuznets curve?. *Energy Policy*, *37*(3), 861–867.

Aldy, J. E. (2005). An environmental Kuznets curve analysis of US state-level carbon dioxide emissions. *The Journal of Environment & Development*, *14*(1), 48–72.

Apergis N, & Ozturk, I. (2015). Testing environmental Kuznets curve hypothesis in Asian countries. *Ecological Indicators, 52*, 16–22.

Apergis, N., & Payne, J. E. (2010). The emissions, energy consumption, and growth nexus: Evidence from the Commonwealth of Independent States. *Energy Policy*, *38*(1), 650–655.

Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Folke, C., Holling, C. S., & Pimentel, D. (1995). Economic growth, carrying capacity, and the environment. *Ecological Economics*, *15*(2), 91–95.

Beckerman, W. (1995). Economic growth and the environment: Whose growth? Whose environment?. In *Growth, the Environment and the Distribution of Incomes* (pp. 275–290). Cheltenham: Edward Elgar Publishing.

Bölük, G., & Mert, M. (2015). The renewable energy, growth and environmental Kuznets curve in Turkey: An ARDL approach. *Renewable and Sustainable Energy Reviews*, *52*, 587–595.

Churchill, S. A., Inekwe, J., Ivanovski, K., & Smyth, R. (2018). The environmental Kuznets curve in the OECD: 1870–2014. *Energy Economics*, *75*, 389–399.

Cole, M. A., Rayner, A. J., & Bates, J. M. (1997). The environmental Kuznets curve: An empirical analysis. *Environment and Development Economics*, *2*(4), 401–416.

Day, K. M., & Grafton, R. Q. (2003). Growth and the environment in Canada: An empirical analysis. *Canadian Journal of Agricultural Economics/Revue Canadienne D'agroeconomie*, *51*(2), 197–216.

Destek, M. A., & Sinha, A. (2020). Renewable, non-renewable energy consumption, economic growth, trade openness and ecological footprint: Evidence from Organisation for Economic Co-operation and Development countries. *Journal of Cleaner Production*, *242*, 118537.

Dijkgraaf, E., & Vollebergh, H. R. (2005). A test for parameter homogeneity in CO_2 panel EKC estimations. *Environmental and Resource Economics*, *32*, 229–239.

Dinda, S. (2004). Environmental Kuznets curve hypothesis: A survey. *Ecological Economics*, *49*(4), 431–455.

Dogan, E., & Seker, F. (2016). The influence of real output, renewable and non-renewable energy, trade and financial development on carbon emissions in the top renewable energy countries. *Renewable and Sustainable Energy Reviews*, *60*, 1074–1085.

Dong, B., Wang, F., & Guo, Y. (2016). The global EKCs. *International Review of Economics & Finance*, *43*, 210–221.

Fakher, H. A., Ahmed, Z., Acheampong, A. O., & Nathaniel, S. P. (2023). Renewable energy, nonrenewable energy, and environmental quality nexus: An investigation of the N-shaped environmental Kuznets curve based on six environmental indicators. *Energy*, *263*, 125660.

Farooq, U., Bhanja, N., Rather, S. R., & Dar, A. B. (2024). From pollution to prosperity: Using inverted N-shaped environmental Kuznets curve to predict India's environmental improvement milestones. *Journal of Cleaner Production*, *434*, 140175.

Fodha, M., & Zaghdoud, O. (2010). Economic growth and pollutant emissions in Tunisia: An empirical analysis of the environmental Kuznets curve. *Energy Policy*, *38*(2), 1150–1156.

Fosten, J., Morley, B., & Taylor, T. (2012). Dynamic misspecification in the environmental Kuznets curve: Evidence from CO_2 and SO_2 emissions in the United Kingdom. *Ecological Economics*, *76*, 25–33.

Galeotti, M., & Lanza, A. (1999). Richer and cleaner? A study on carbon dioxide emissions in developing countries. *Energy Policy*, *27*(10), 565–573.

Galeotti, M., Lanza, A., & Pauli, F. (2006). Reassessing the environmental Kuznets curve for CO2 emissions: A robustness exercise. *Ecological Economics*, *57*(1), 152–163.

Georgiev, E., & Mihaylov, E. (2015). Economic growth and the environment: Reassessing the environmental Kuznets curve for air pollution emissions in OECD countries. *Letters in Spatial and Resource Sciences*, *8*(1), 29–47.

Gill, A. R., Viswanathan, K. K., & Hassan, S. (2018). A test of environmental Kuznets curve (EKC) for carbon emission and potential of renewable energy to reduce greenhouse gases (GHG) in Malaysia. *Environment, Development and Sustainability*, *20*, 1103–1114.

Grossman, G. M., & Krueger, A. B. (1991). Environmental impacts of a North American Free Trade Agreement (Working Paper No. 3914). National Bureau of Economic Research.

Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. The quarterly journal of economics, 110(2), 353-377.

He, J., & Richard, P. (2010). Environmental Kuznets curve for CO_2 in Canada. *Ecological Economics*, *69*(5), 1083–1093.

Hill, R. J., & Magnani, E. (2002). An exploration of the conceptual and empirical basis of the environmental Kuznets curve. *Australian Economic Papers*, *41*(2), 239–254.

Hoechle, D. (2007). Robust standard errors for panel regressions with cross-sectional dependence. *The Stata Journal*, *7*(3), 281–312.

Holtz-Eakin, D., & Selden, T. M. (1995). Stoking the fires? CO_2 emissions and economic growth. *Journal of Public Economics*, *57*(1), 85–101.

Huang, J., Zhang, D., Zhang, Z., Kong, W., Yan, J., & Xia, F. (2023). Trapped in dilemma: Inverted N-shaped EKC evidence of economic growth and ecological land in a spatial spillover perspective. *Applied Geography*, *161*, 103145.

Intergovernmental Panel on Climate Change. (2023). *Climate change 2023: Synthesis report, summary for policymakers: Contribution of Working Groups I, II, and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Core Writing Team, H. Lee & J. Romero, Eds.). IPCC.

Isik, C., Ongan, S., Ozdemir, D., Ahmad, M., Irfan, M., Alvarado, R., & Ongan, A. (2021). The increases and decreases of the environment Kuznets curve (EKC) for 8 OECD countries. *Environmental Science and Pollution Research*, *28*, 28535–28543.

Jalil, A., & Mahmud, S. F. (2009). Environment Kuznets curve for CO_2 emissions: A cointegration analysis for China. *Energy Policy*, *37*(12), 5167–5172.

Jebli, M. B., Youssef, S. B., & Ozturk, I. (2016). Testing environmental Kuznets curve hypothesis: The role of renewable and non-renewable energy consumption and trade in OECD countries. *Ecological Indicators*, *60*, 824–831.

Jones, M. W., Peters, G. P., Gasser, T., Andrew, R. M., Schwingshackl, C., Gütschow, J., ... & Le Quéré, C. (2023). National contributions to climate change due to historical emissions of carbon dioxide, methane, and nitrous oxide since 1850. Scientific Data, 10(1), 155.

Karim, S., Appiah, M., Naeem, M. A., Lucey, B. M., & Li, M. (2022). Modelling the role of institutional quality on carbon emissions in Sub-Saharan African countries. *Renewable Energy*, *198*, 213–221.

Kaul, I., Grunberg, I., & Stern, M. (1999). *Global Public Goods.* New York: Oxford.

Kuznets, S. (1955). Economic growth and income inequality. *American Economic Review, 45*(1), 1–28.

Lau, L. S., Choong, C. K., Ng, C. F., Liew, F. M., & Ching, S. L. (2019). Is nuclear energy clean? Revisit of environmental Kuznets curve hypothesis in OECD countries. *Economic Modelling*, *77*, 12–20.

Leal, P. H., & Marques, A. C. (2020). Rediscovering the EKC hypothesis for the 20 highest CO_2 emitters among OECD countries by level of globalization. *International Economics*, *164*, 36-47.

Leal, P. H., & Marques, A. C. (2022). The evolution of the environmental Kuznets curve hypothesis assessment: A literature review under a critical analysis perspective. *Heliyon*, *8*(11).

Li, K., & Lin, B. (2015). Impacts of urbanization and industrialization on energy consumption/ CO_2 emissions: Does the level of development matter?. *Renewable and Sustainable Energy Reviews*, 52, 1107–1122.

Lin, B., Omoju, O. E., & Okonkwo, J. U. (2015). Impact of industrialisation on CO_2 emissions in Nigeria. *Renewable and Sustainable Energy Reviews*, *52*, 1228–1239.

Lorente, D. B., & Álvarez-Herranz, A. (2016). Economic growth and energy regulation in the environmental Kuznets curve. *Environmental Science and Pollution Research*, *23*, 16478–16494.

Magnani, E. (2001). The environmental Kuznets curve: Development path or policy result?. *Environmental Modelling & Software*, *16*(2), 157–165.

Moomaw, W. R., & Unruh, G. C. (1997). Are environmental Kuznets curves misleading us? The case of CO_2 emissions. *Environment and Development Economics*, *2*(4), 451–463.

Nasir, M. A., Canh, N. P., & Le, T. N. L. (2021). Environmental degradation & role of financialisation, economic development, industrialisation and trade liberalisation. *Journal of Environmental Management*, *277*, 111471.

Nasr, A. B., Gupta, R., & Sato, J. R. (2015). Is there an environmental Kuznets curve for South Africa? A co-summability approach using a century of data. *Energy Economics*, *52*, 136–141.

Nasreen, S., Anwar, S., & Ozturk, I. (2017). Financial stability, energy consumption and environmental quality: Evidence from South Asian economies. *Renewable and Sustainable Energy Reviews*, *67*, 1105–1122.

Naveed, A., Ahmad, N., Aghdam, R. F., & Menegaki, A. N. (2022). What have we learned from environmental Kuznets curve hypothesis? A citation-based systematic literature review and content analysis. *Energy Strategy Reviews*, *44*, 100946.

Ng, C. F., Choong, C. K., Ching, S. L., & Lau, L. S. (2019). The Impact of electricity production from renewable and non-renewable sources on CO_2 emissions: Evidence from OECD countries. *International Journal of Business & Society, 20*(1).

Özokcu, S., & Özdemir, Ö. (2017). Economic growth, energy, and environmental Kuznets curve. *Renewable and Sustainable Energy Reviews*, *72*, 639–647.

Ozturk, I., & Acaravci, A. (2013). The long-run and causal analysis of energy, growth, openness and financial development on carbon emissions in Turkey. *Energy Economics*, *36*, 262–267.

Panayotou, T. (1993). *Empirical tests and policy analysis of environmental degradation at different stages of economic development* (ILO Working Paper WP 238). Technology and Employment Programme, International Labour Organization.

Panayotou, T. (1997). Demystifying the environmental Kuznets curve: Turning a black box into a policy tool. *Environment and Development Economics*, *2*(4), 465–484.

Pesaran, M. H. (2004). *General diagnostic tests for cross section dependence in panels* (Cambridge Working Papers in Economics No. 0435). Faculty of Economics, University of Cambridge.

Salman, M., Long, X., Dauda, L., & Mensah, C. N. (2019). The impact of institutional quality on economic growth and carbon emissions: Evidence from Indonesia, South Korea and Thailand. *Journal of Cleaner Production*, *241*, 118331.

Shahbaz, M., Mutascu, M., & Azim, P. (2013). Environmental Kuznets curve in Romania and the role of energy consumption. *Renewable and Sustainable Energy Reviews*, *18*, 165–173.

Sinha, A., & Sen, S. (2016). Atmospheric consequences of trade and human development: A case of BRIC countries. *Atmospheric Pollution Research*, *7*(6), 980–989.

Sinha, A., Shahbaz, M., & Balsalobre, D. (2018). *N-shaped environmental Kuznets curve: a note on validation and falsification* (MPRA Paper No. 99313).

Tamazian, A., & Rao, B. B. (2010). Do economic, financial and institutional developments matter for environmental degradation? Evidence from transitional economies. *Energy Economics*, *32*(1), 137–145.

Ullah, A., Dogan, M., Pervaiz, A., Bukhari, A. A. A., Akkus, H. T., & Dogan, H. (2024). The impact of digitalization, technological and financial innovation on environmental quality in OECD countries: Investigation of N-shaped EKC hypothesis. *Technology in Society*, *77*, 102484.

Vollebergh, H. R., Dijkgraaf, E., & Melenberg, B. (2005). *Environmental Kuznets curves for CO_2: Heterogeneity versus homogeneity* (CentER Discussion Paper Series No. 2005-25). http://dx.doi.org/10.2139/ssrn.683109

Wang, Q., Li, Y., & Li, R. (2024). Rethinking the environmental Kuznets curve hypothesis across 214 countries: The impacts of 12 economic, institutional, technological, resource, and social factors. *Humanities and Social Sciences Communications*, *11*(1), 1–19.

World Bank. (2024). The Worldwide Governance Indicators. https://info.worldbank.org/governance/wgi/

World Bank. (2024). World Development Indicators. https://databank.worldbank.org/source/worlddevelopment-indicators.

Yaduma, N., Kortelainen, M., & Wossink, A. (2015). The environmental Kuznets curve at different levels of economic development: A counterfactual quantile regression analysis for CO_2 emissions. *Journal of Environmental Economics and Policy*, *4*(3), 278–303.

Yavuz, N. Ç. (2014). CO_2 emission, energy consumption, and economic growth for Turkey: Evidence from a cointegration test with a structural break. *Energy Sources, Part B: Economics, Planning, and Policy*, *9*(3), 229–235.

Zafar, A., Ullah, S., Majeed, M. T., & Yasmeen, R. (2020). Environmental pollution in Asian economies: Does the industrialisation matter?. *OPEC Energy Review*, *44*(3), 227–248.

Received: September, 09, 2024
Accepted: December, 29, 2024

APPENDIX

Table A1. Estimation results of FE and RE with DK standard error approach – dependent variable CO_2 (advanced economies)

DV: $LNCO_2$	DK-FE				DK-RE		
	Coef.	Std.Err.	Prob.		Coef.	Std.Err.	Prob.
LNGDP	-173.404*	18.506	0.000		-178.536*	15.767	0.000
LNGDP2	16.863*	1.789	0.000		17.355*	1.535	0.000
LNGDP3	-0.545*	0.058	0.000		-0.560*	0.050	0.000
REN	-1.277*	0.151	0.000		-1.207*	0.189	0.000
NREN	0.523*	0.107	0.000		0.484*	0.117	0.001
LRL	-0.280***	0.137	0.055		-0.248	0.148	0.109
IND	0.569***	0.314	0.085		0.639	0.401	0.128
_cons	595.217*	63.302	0.000		612.956*	53.605	0.000
Observations	558				558		
N	28				28		
(Prob> Chi2)	0.0058						

*, **, and *** denote significance at the 1%, 5%, and 10% levels, respectively.

Table A2. Estimation results of FE and RE with DK standard error approach – dependent variable GH (advanced economies)

DV: GH	DK-FE				DK-RE		
	Coef.	Std.Err.	Prob.		Coef.	Std.Err.	Prob.
LNGDP	-164.206*	16.799	0.000		-164.043*	20.019	0.000
LNGDP2	15.824*	1.623	0.000		15.809*	1.919	0.000
LNGDP3	-0.506*	0.052	0.000		-0.506*	0.061	0.000
REN	-1.430*	0.164	0.000		-1.450*	0.113	0.000
NREN	0.194**	0.077	0.020		0.211	0.136	0.137
LRL	-0.470*	0.124	0.001		-0.473*	0.121	0.001
IND	0.316	0.250	0.222		0.302	0.268	0.274
_cons	579.386*	57.719	0.000		578.790*	69.308	0.000
Observations	558				558		
N	28				28		
Prob> Chi2	0.0011						

*, **, and *** denote significance at the 1%, 5%, and 10% levels, respectively.

Table A3. Estimation results of FE and RE with DK standard error approach – dependent variable CO$_2$ (emerging economies)

DV: LNCO$_2$	DK-FE				DK-RE		
	Coef.	Std.Err.	Prob.		Coef.	Std.Err.	Prob.
LNGDP	1.518	1.468	0.314		6.518	3.988	0.119
LNGDP2	-0.228	0.301	0.459		-1.481***	0.796	0.078
LNGDP3	0.011	0.015	0.492		0.079***	0.040	0.064
REN	-4.654*	0.561	0.000		-2.110*	0.250	0.000
NREN	-1.784*	0.597	0.008		2.168*	0.589	0.002
LRL	0.079***	0.043	0.081		0.810*	0.056	0.000
IND	0.941**	0.337	0.012		2.736*	0.343	0.000
_cons	-	-	-		-	-	-
Observations	100				100		
N	5				5		
Prob> Chi2	0.000						

*, **, and *** denote significance at the 1%, 5%, and 10% levels, respectively.

Table A4. Estimation results of FE and RE with DK standard error approach – dependent variable GH (emerging economies)

DV: GH	DK-FE				DK-RE		
	Coef.	Std.Err.	Prob.		Coef.	Std.Err.	Prob.
LNGDP	3.354***	1.745	0.070		13.058**	5.156	0.020
LNGDP2	-0.263	0.358	0.472		-2.399**	1.009	0.028
LNGDP3	0.006	0.018	0.745		0.118**	0.049	0.028
REN	-4.855*	0.666	0.000		2.822*	0.622	0.000
NREN	-1.377**	0.713	0.068		9.302*	0.362	0.000
LRL	0.093	0.057	0.121		-1.314*	0.143	0.000
IND	1.29*	0.385	0.003		2.246**	0.835	0.015
_cons	-	-	-		-	-	-
Observations	100				100		
N	5				5		
Prob> Chi2	0.000						

*, **, and *** denote significance at the 1%, 5%, and 10% levels, respectively.