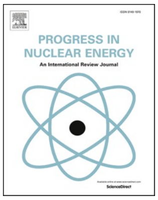
Progress in Nuclear Energy 178 (2025) 105526

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene



Nuclear energy utilization and the expectations of emission-reduction gains: Empirical evidence from economic trajectory of selected utilizing states

Şeyma Bozkaya [a], Stephen Taiwo Onifade [b,*], Mahmut Sami Duran [c]

[a] Medipol University, International Trade and Finance Department, 34820, İstanbul, Türkiye
[b] School of Finance and Accounting, Economics Department, University of Vaasa, FI-65200, Vaasa, Finland
[c] Department of Banking and Finance, Selçuk University, Konya, Turkey

ARTICLE INFO

JEL classification:
P18
013
044
C80

Keywords:
Nuclear energy
Environmental quality
Heterogenous panel analysis
The EKC conjecture
Economic growth

ABSTRACT

As the global quest for clean energy grows, the environmentally friendly nature of nuclear energy as a potential non-fossil energy source is generating interest around the world. Therefore, we examine whether nuclear energy utilization has significantly driven carbon emission reduction among the utilizing states. Empirical analyses were conducted using second-generation techniques. The analyses conducted also incorporated testing the EKC theory, as well as examining the effects of natural resources and economic growth on emissions in the sample countries. The empirical analyses cover data from 2000 to 2020 for a total of 27 nuclear energy-using countries as obtained from the Statistical Review of World Energy (Bp, 2021). The findings show that neither the use of nuclear energy nor natural resources significantly reduces carbon emissions across the countries. Additionally, the EKC hypothesis of reduction in emission levels as income expands beyond a certain threshold does not hold for the countries. Moreover, the causality analysis shows that there is a one-way causality from emissions to nuclear energy use. These findings thus highlight the need for more research on how to minimize the indirect carbon footprint that is associated with nuclear energy utilization.

1. Introduction

Given the continuous increase in the economic growth targets of countries around the world, global energy demand has witnessed a steady increase year after year. In addition, people's desire for modern living has also increased the need for energy use and the environmental consequences of this development have also increased. Although most economies aspire to transition to green energy for sustainable development, however, this goal may be difficult to achieve. This is because the global energy production from renewable energy sources at the moment is not enough to meet the world's total energy demand. Thus, the world continues to depend on fossil fuels in the meantime. Meanwhile, this dependence on fossil fuels is seen as the biggest cause of global warming and climate change.

Estimates by the International Atomic Energy Agency (IAEA) show that almost two-thirds of total greenhouse gas emissions are a result of energy production and consumption (IAEA, 2018). Large amounts of greenhouse gas emissions are seen as one of the main causes of global warming (Ozturk, 2017; Danish et al., 2022; Sharif et al., 2021; Hao, 2022). According to US Energy Information Administration (EIA) statistics, the cumulative increase in global carbon emissions between 1990 and 2019 reached approximately 63.9%. By 2030, this amount is expected to increase by more than 45% compared to the 2000s, and fossil energy consumption is generally shown as the main source of this increase (Inglesi-Lotz and Dogan, 2018; Hoa et al., 2022; Apergis and Payne, 2017). Today, global warming caused by the increase in greenhouse gas emissions has become a serious threat to economic, social, and environmental sustainability. As such, several studies have called for serious measures to address the rising menace (Dogan and Ozturk, 2017; Onifade and Alola, 2023; Appiah et al., 2023).

Given the current pace of industrialization, modernization, growth, and development, the rate of global energy supply is likely to double from 2016 to 2030 (Sarkodie & 76 Adams, 2018). This intense energy demand points to a higher tendency of having an increase in the periods in which climate change-associated problems will become more alarming. Such problems include the rise in sea levels, decrease in

---

* Corresponding author.

E-mail addresses: seyma.bozkaya@medipol.edu.tr (Ş. Bozkaya), stephen.onifade@uwasa.fi (S.T. Onifade), msduran@selcuk.edu.tr (M.S. Duran).

https://doi.org/10.1016/j.pnucene.2024.105526
Received 4 December 2023; Received in revised form 19 October 2024; Accepted 2 November 2024

freshwater resources, rapid melting of polar ice caps, serious conditions in weather outlooks, fast rate of disease penetration, and loss of biological diversity among others (Danish et al., 2017). For this reason, in order to ensure energy supply security and to create a more livable world, turning to the use of clean energy throughout the world will be vital for the survival of lives in the next centuries. In this respect, it will be very crucial to stimulate accessibility to clean energy sources as a way of reducing carbon dioxide (CO_2) emissions. Doing this would help the world to bring into reality the various desires for global sustainable growth, as enshrined in the targets of various environmental summits (the Paris Accord, the COPs, and other SDGs goals).

Given the recent Covid-19 pandemic and the ongoing Ukraine-Russia War, the attention of the global community has been further drawn to the importance of energy use as energy-related problems such as energy deprivation, increase in energy prices, inflation and disruption in supply chains continue to rise. This thus demonstrates the fact that countries need to reconsider their energy investments and look towards increasing their renewable portfolios. Although there have been differences in the rates of adoption of renewable across countries, it is noteworthy that many countries have been accelerating their renewable energy policies and taking steps to reduce dependence on energy imports. It has been noted that about 66.6% of the global primary energy supply could be provided by renewable energy sources by 2050 (Hassan et al., 2024). While the importance of renewable energy and related technological innovations is increasing, the relatively environmentally friendly nature of nuclear energy has also been drawing some attention to this type of energy source (Wang et al., 2023; Duran et al., 2022; Bozkaya et al., 2022). Also, investments in nuclear energy and renewable resources are now increasing in many countries including among the developing nations (Jewell, 2011).

Nuclear energy is known as a type of energy with very low average life-cycle carbon dioxide equivalent emissions. While nuclear power generation decreased in 2020 due to the pandemic, it however recovered as the effect of the epidemic slowed down in the following periods and increased by 100 TWh to reach 2653 TWh in 2021 (World Nuclear Association, 2022). Although the year-end capacity of the world's nuclear reactors increased in 2021, the total number of reactors was 436 in 2020, with about five reactors down. On the other hand, the total capacity of reactors generating electricity in 2021 was 370 GWe, an increase of 1 GWe compared to 2020. This figure represents the highest total capacity ever of reactors producing electricity in a year (World Nuclear Association, 2022). In a nutshell, the interest in nuclear energy and its production capacity is growing thereby attracting more discussions among researchers in the expanding environmental literature.

Many studies on environmental quality in the literature have their theoretical foundations rooted in various hypotheses such as the EKC hypothesis. The origin of the Kuznets curve dates back to the work of Kuznets (1955) and thereafter the EKC hypothesis has been expounded and applied in many other early studies (Grossman and Krueger, 1991). The hypothesis symbolizes an inverted "U-shaped" nexus that income has with environmental degradation (Onifade, 2022). Many empirical studies have produced evidence of potential negative environmental externalities of economic growth as the level of total conventional energy consumption rises in a country (Hao and Chen, 2023; Tsimisaraka et al., 2023; Li et al., 2023). However, the EKC assumption suggests that higher levels of economic growth will increase environmental degradation in the early stages of a country's economic development, but the negative impact will diminish over time as a certain income threshold is reached. Therefore, testing the EKC hypothesis is common in many empirical studies. However, most of these studies have only concentrated on the fossil energy facets by focusing on oil, gas, and coal in analyzing the EKC conjecture. Besides, as the global quest for clean energy is increasing, the relatively environmentally friendly nature of nuclear energy essentially calls for an in-depth analysis within the EKC conjecture. Therefore, this study investigates the environmental impacts of nuclear energy in nuclear energy-consuming economies. It also tests the validity of the EKC hypothesis in the sample countries. In order to control for the environmental impacts of resource endowment, the natural resource variable is included in the model. Overall, the study consists of five sections, starting with the introduction in the first section. The second section of the study presents a broad literature on the relationship between nuclear energy consumption and growth. The third section highlights the dataset and methodology of the study, while the fourth section explains the results obtained from the analysis. The last section of the study consists of conclusions and general recommendations.

2. An overview of current literature

It is a general convention that the increase in the use of nuclear energy and renewable energy sources is effective in combating climate change by limiting the amount of CO_2 emissions. However, when we evaluate the literature, we observe that the related studies in this field are not in consensus as the results differ. Apergis and Payne (2010) investigated the relationship between nuclear energy consumption and CO_2 emissions in 19 developed and developing economies. Larsson panel co-integration means were combined with the VEC method in that study using the data set between 1984 and 2007. The findings from the study show that nuclear energy consumption enhances environmental sustainability in the long run through the reduction in CO_2 emission levels. Furthermore, they observed that there is a mutual causality relationship between the emission levels and the rate of nuclear energy utilization. Iwata et al. (2010) investigated the effect of nuclear energy consumption on CO_2 emissions in France. The findings of the study covering periods from the 1960s up until the early 2000s indicate that nuclear energy consumption is inversely associated with the emissions rate in the long term. This thus further supports Apergis and Payne (2010) conclusion that nuclear energy consumption enhances environmental sustainability. Chang (2010) examined the relationship between nuclear energy consumption, growth, and emission levels in China using data sets from 1981 to 2006. In the study, the Johansen method of cointegration was followed to establish that nuclear energy consumption and carbon emission levels positively influence growth in the long term. In addition, Chang (2010) observed there is a unidirectional causality running from nuclear energy consumption to both emissions levels and economic growth levels in the study.

Menyah and Wolde-Rufael (2010) in another clime also investigated the causality relationship between carbon dioxide (CO_2) emissions, nuclear energy consumption, and GDP variables in the US economy between 1960 and 2007. It was gathered that nuclear energy use helps to cut down emissions rates. The study also used the Granger causality test to affirm a one-way causality relationship from nuclear usage to CO_2 emissions. Baek and Pride (2014) checked the same relationship with a set of 6 economies that are using nuclear energy. The concluding outputs divulge that nuclear usage lessens the emission from energy use. The results here were reached via the CVAR technique of data analysis.

In a different framework of analysis, Al-Mulali (2014) also used nuclear energy when looking at GDP growth and CO_2 emission linkages in a combined 30 main nuclear-consuming states. Panel FMOLS and Granger causality tests were used for the evaluations. Nuclear energy use was been found to have a growth-inducing effect in the long run. While there is causality from this energy type to growth, there is a unidirectional causal link from carbon emissions to nuclear energy use. Baek (2016) also looked at the dynamic effects of nuclear and renewable energy consumption on CO_2 emissions. The study, which used datasets between 1960 and 2010, considers the USA as a sample country. The results of the study using the ARDL analysis method support the EKC hypothesis in the short term. CO2 emissions are found to increase in the long run. As a result, it is concluded that energy consumption increases emissions.

Jin and Kim (2018) set out to assess the influencer forces behind carbon emissions. They assessed thirty nuclear energy-adopting states just as Al-Mulali (2014) did. However, unlike the latter, their outcomes were divergent in the sense that the evidence for emission abatement was only from renewable energy rather than the earlier confirmed nuclear-emission abatement effects. For Lau et al. (2019), the analysis of the environmental impacts of nuclear energy use is evaluated in about eighteen OECD countries between the mid-1990s and the mid-2020s following the application of Panel GMM and Panel FMOLS methods. They eventually established that nuclear energy plays a crucial role in environmental protection. Their stance is supported by the results of Saidi and Omri (2020), who argue for CO2 reduction effects from nuclear energy use in a combination of other OECD economies. The only difference between these two studies is the methods used, as the second study applies the VECM rather than the GMM estimator. Pilatowska et al. (2020) investigated the effect of nuclear energy consumption and renewable energy consumption on emissions in Spain in their study covering the period between 1970 and 2018. Findings from the study using Granger causality and TVAR analyses showed that both nuclear and renewable energy consumption contributed to the reduction of emissions. Bandyopadhyay and Rej (2021) analyzed the Indian economy between 1978 and 2019.

In other very recent studies, Cakar et al. (2022) investigated the outcomes of improved nuclear energy technologies on general carbon emission levels in G7 countries between 1970 and 2015. When the results of the Panel Threshold Regression Model are evaluated according to a certain range of innovation levels, there is evidence that increased innovation in nuclear energy reduces carbon emissions in the G7. Therefore, it is concluded that increasing technological innovation related to nuclear energy will improve environmental quality. In another study, a combination of ten developing states was used to examine the nuclear-emissions effects by Naimoğlu (2022). The environmentally beneficial nuclear-emissions nexus was equally upheld. Most recently, a few other studies have equally upheld the environmentally beneficial nuclear-emissions nexus like Danish et al. (2022), and Pata and Kartal (2022) for the OECD and South Korea respectively.

2.1. Contributions & merits of study

Following the EKC hypothesis, the direction of a country's worsening environmental degradation path can be changed after income growth reaches a certain threshold. Attaining this turning point in environmental degradation may be possible through various channels such as changes in energy sources and technological transformation among others. Numerous studies have tested the EKC hypothesis when investigating the environmental impacts of energy sources. However, the vast majority of these empirical studies have focused on fossil energy sources such as oil, gas and coal. In this study, however, we reconsider the EKC conjecture by scrutinizing the environmental impact of nuclear energy consumption to examine whether this energy form is yielding the expected carbon emission-reduction gains. Additionally, the empirical approach utilized in the study also addresses the challenges of cross-sectional dependence in the extant studies.

3. Data, model description and method

The sample countries to be used for the empirical analysis are globally distributed, mostly nuclear energy-consuming countries, as shown in the BP World Energy Statistical Review 2021 report. A sample group of 27 countries consisting of Germany, Brazil, Canada, China, France, India, Japan, Mexico, Russia, Argentina, South Korea, South Africa, Belgium, Czech Republic, Finland, Hungary, Netherlands, Romania, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom, Pakistan, and the United States of America (USA) were considered. The analyses were conducted on annual data settings from 2000 to 2020 and the variables are in logarithmic scale. The broad definitions of the variables in the model and their source data are presented in Table 1. CO2 was used as the independent variable in the model to represent environmental degradation.

Table 1
Variable description.

Variable	Broad Definition of Variable	Measurement	Source
$LnCO_2$	The CO2 here only reflects emissions resulting from the fossil resource-based consumptions (i.e. the combustion of oil, gas, and coal).	Million tonnes of carbon dioxide	BP Stat
LnNÜK	This is assessed with respect to the total production but excludes the cross-border supply of electricity. "Input-equivalent" here refers to the quantity of fuels needed to produce electricity by the thermal power plants.	input-equivalent of fuels	BP Stat
LnGDPpc	GDP per capita is gross domestic product divided by mid-year population.	constant 2015 US$	WDI
LnNATR	Total natural resources rents are the sum of oil rents, natural gas rents, coal rents (hard and soft), mineral rents, and forest rents.	% of GDP	WDI

Where: WDI is for the World Development Indicators while BP represents the British petroleum.

3.1. Model specification and Methodological Framework

The model to be estimated is based on Cakar et al. (2022), Naimoğlu (2022), Gyamfi et al. (2021), and Jahanger et al. (2023) and is shown in equation (1);

$$LnCO_{2it} = \beta_0 + \beta_1 LnGDPpc_{i,t} + \beta_2 LnGDPpc2_{it} + \beta_3 LnN\ddot{U}K_{i,t} + \beta_4 LnNATR_{it} + u_{it} \tag{1}$$

The 'β's here are used to represent the slopes in equation (1), except for the β_0 (intercept), while *i,t* represents the horizontal section(s) and the subsequent time. '*u*' represents the error term. In order to interpret the effects of the variables used in the analysis as elasticity, their natural logarithmic forms were used. It has been empirically proven by many studies that economic growth leads to carbon emissions and thus has environmental damage (Aye and Edoja, 2017; Bozkaya et al., 2023; Hao and Chen, 2023; Tsimisaraka et al., 2023). Therefore, it is included as a variable in the model to observe the possible effects of growth on the sample group considered in the study. Also, in order to test the EKC hypothesis, GDP per capita and the square estimates were incorporated into the model. Nuclear energy is considered an environmentally friendly energy source compared to fossil energy sources (Usman et al., 2022; Hassan et al., 2023; Zhang et al., 2023). Therefore, the indicator for nuclear energy consumption is included in the model to observe its environmental impacts. The impact of natural resources on carbon emissions can vary greatly depending on a country's energy policies and how natural resource rents are used. The observations of studies that have empirically investigated the impact of this variable vary (Sadorsky, 2011; Al-mulali, Saboori and Ozturk, 2015; Onifade, 2023; Adams and Acheampong, 2019). Overall, most studies observed that channeling resource revenues to the production and consumption of fossil fuels directly contributes to carbon emissions, while redirecting resource revenues to green energy has the potential to reduce emissions. Fig. 1 illustrates the methodological roadmap of the study.

In the empirical application, firstly, the CD test was applied to determine the cross-sectional dependence between cross-sections. Testing the cross-sectional dependence between units is highly influential on the results to be achieved (Breusch and Pagan, 1980; Pesaran, 2004). Therefore, it is important to examine whether the model has a horizontal cross-section in the series before proceeding to coefficient estimation to ensure that the results to be obtained are more consistent. The presence of cross-section dependence is detected by the

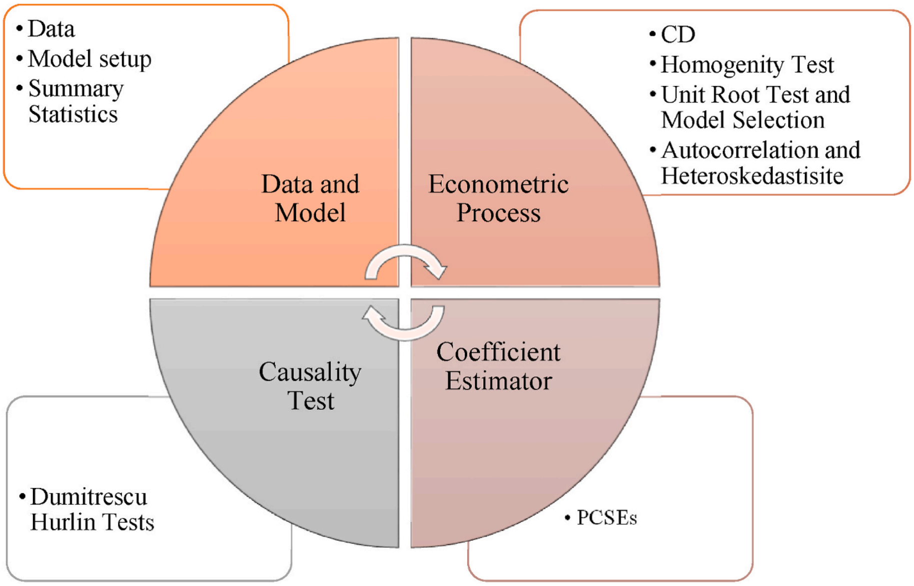


Fig. 1. Methodological framework.
Source: Authors' design

Breusch-Pagan (1980) Lagrange Multiplier (LM) test when the time dimension of the panel is larger than the cross-section dimension; are tested with the Pesaran (2004) CD test when both are large. Since there are 27 countries and 21 years in this study, the CD test statistic results are used. The CD test is used when N > T. Equation (2) estimated for the CD test is as follows (Breusch and Pagan, 1980).

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} T\widehat{p}_{ij}\right) \tag{2}$$

After the CD test was applied, the CADF test developed by Pesaran (2007), one of the second-generation unit root tests, was used after determining the existence of the cross-section. The CADF test allows unit root testing to be performed on each cross-section unit (for each country) in the series that make up the panel. Thanks to this advantage, the stationarity of the series can be calculated for the panel as a whole and for each horizontal section separately. The CADF test, which assumes that each country is affected differently by time effects and takes into account spatial autocorrelation, is used in conditions where both T > N and N > T are valid. The CADF test statistic is estimated as seen in Equation (3).

$$\Delta y_{it} = \mu_i + \omega_i t + \alpha_i y_{i,t-1} + v_i \overline{y}_{t-1} + \sum_{j=1}^{P_i} \lambda_{ij} \Delta y_{i,t-j} + \sum_{j=0}^{P_i} \overline{\omega}_{ij} \Delta \overline{y}_{t-j} + \varepsilon_{it} \tag{3}$$

In the equation, $\overline{y}_t$ denotes the mean of the cross-sections and also represents the effects of the unobservable common factor with the inclusion of the cross-section-specific delayed mean ($\overline{y}_{t-1}$) and the difference $\left(\Delta\overline{y}_{t-j}\right)$ into the equation.

The Panel Corrected Standard Errors (PCSEs) method was used to estimate the coefficient after the unit root test. Since T = 21<N = 27 in the study, it was not suitable for many alternative methods (such as CCE, and CS-ARDL), which led to the lack of consistent results. In addition, since the model used in the study has cross-sectional dependence, autocorrelation, and varying variance problems, the PCSEs method was preferred because it gives consistent results under the presence of these problems (Moundigbaye et al., 2018; Mkombe et al., 2021; Zahariadis et al., 2022; Oluwatobi et al., 2022). PCSEs retain the weighting of observations (Prais-Winsten) for autocorrelation. However, it uses an estimator to include its sensitivity to cross-section dependence when calculating standard errors (Moundigbaye et al., 2018). This method considers the standard errors and when calculating the variance-covariance estimation, the distortions are by default heteroscedastic and correlate simultaneously across panels (Chen et al., 2006). It has been stated that the PCSE estimation method gives reliable results even when conditions of extremely high varying variance and simultaneous correlation of errors prevail (Beck and Katz, 1995). While it is supported that the Feasible Generalized Least Squares (FGLS) method gives more consistent results when T/N > 1.50, Moundinbaye et al. (2018) assume that the PCSE estimator gives better results for the test when both 1.50<T/N and T/N < 1.50. In our study, the PCSEs method was preferred since T = 21, N = 27, and T/N = 0.77 < 1.50. The two-stage estimator formulas of Beck and Katz (1995) for the PCSEs estimator are highlighted in Equation (4) and Equation (5).

$$\widehat{\beta} = (\widetilde{X}'\widetilde{X})^{-1}\widetilde{X}'\widetilde{y} \tag{4}$$

$$Var(\widehat{\beta}) = (\widetilde{X}''\widetilde{X})^{-1}(\widetilde{X}'\widehat{\Sigma}'\widetilde{X})(\widetilde{X}'\widetilde{X})^{-1} \tag{5}$$

$\widetilde{X}$ and $\widetilde{y}$, in the equations represent Prais-transformed vectors of explanatory and dependent variables.

After the coefficient estimation, the causality test was performed to determine the direction of the causal relationship between the dependent variable and the independent variables. In our study, the Dumitrescu-Hurlin Panel causality test applied to heterogeneous panels was used because the slope coefficients of the variables used in the model were heterogeneous and there was no cointegration relationship between the variables. To use this causality test, there is no prerequisite for the existence of a cointegration relationship. In addition, to use this test, all of the variables must be stationary at the level. This test was applied by taking the difference of the variables that did not become stationary at the level. In their study, Dumitrescu and Hurlin (2012) stated that the causality relationship in question for any country within the scope of panel data is also valid for different countries, and it gives more effective results when the number of observations increases. This test also provides effective results even when the time dimension is larger or smaller than the slice dimension. The causality test model is defined in Equation (6) following (Dumitrescu and Hurlin, 2012).

$$Y_{i,t} = \alpha_i + \sum\nolimits_{k=1}^{k} Y_i^{(k)} Y_{i,t-k} + \sum\nolimits_{k=1}^{k} \beta_i^{(k)} X_{i.t-k} + e_{i,t} \tag{6}$$

In equation (6) k; stands for the optimum lag length. This equation is used to determine whether the variable x is the cause of the variable y. The causality relationship is tested using the H_0 hypothesis on the basis of an F test. In case the H_0 hypothesis is rejected, it can be tested whether there is a bidirectional causality relationship by changing the direction of causality by changing the location of the variables (Lopez and Weber, 2017). This test represents the average of individual Wald tests calculated for cross-section units within the framework of the Granger causality test and the test is compatible with both heterogeneity and cross-section dependence.

4. Empirical application results and discussions

The summary statistics of the variables are in Table 2. According to the summary, it can be seen that the number of observations is suitable for the panel data analysis. It is noteworthy that while the minimum value of −2.06 is seen in the LnNATR, the maximum value of about 24.46 was recorded in the LnGDPpc. In addition, it was observed that there was no significant change in standard deviations except for the LnGDPpc2. The corresponding results of the procedural tests are given in the range of tables starting from Tables 3–7.

Table 3 shows the cross-section dependency test results of the variables in the model. According to the results in the table, only the null hypothesis that there is no cross-section in the nuclear energy consumption (LnNÜK) variable was accepted. Other variables, on the other hand, rejected the H_0 hypothesis and accepted the existence of a horizontal section. However, looking at the whole model, since the null hypothesis is rejected according to the results of the test applied for the whole model, the availability of CD in the model is accepted. The unit root test was then conducted, and Table 4 shows the CADF test results. The table contains the results for both fixed and trending options. According to test statistics, $LnCO_2$, LnGDPpc, LnGDPpc2, and LnNATR variables became stationary at the I(1) level, while LnNÜK has the relative stationary state at I(0) level.

To corroborate the stationarity test which is very important in deciding the model to be used, we also check the heterogeneity situation, and the results are presented in Table 5. According to the results of this test, which allows us to decide whether the slope coefficients of the variables used in the model are homogeneous or not, since the p-value is < 0.05, the hypothesis of *H_0: Slope coefficients are homogeneous* was rejected and it was decided that the slope coefficients were heterogeneous. Therefore, given these challenges, the test applied to determine the model to be used in the study was then reported in Table 6. According to the results in the table, the model includes a unit effect (*Test F*) following the Hausman test to decide whether the model to be used is Fixed Effects or Random Effects. Going by the results, it is decided that the Fixed Effects Model is appropriate in line with the probability value.

In addition, if we consider the results in Table 7 showing the Wooldridge and Modified Wald Test results, it can be observed that the model had autocorrelation and varying variance problems and the choice of estimator should be able to accommodate all these issues. Therefore, the PCSEs estimator was used, which gives consistent results under these conditions, since the model includes cross-sectional dependence, autocorrelation, and varying variance. Recall, from the initial result shown in Tables 6 and it was eventually decided that the PCSEs estimations would be more robust and efficient within the framework of the Fixed Effects Model. Besides, this method also stands to be more beneficial, and it is an appropriate estimator since it gives consistent results when $T < N$ and $T/N = 0.77 < 1.50$.

Table 2
Summary statistics of variables.

	Obs.	Mean	Std. Dev.	Min.	Max.
LnCO2	567	2.42826	0.64508	1.063802	3.99535
LnNÜK	567	−0.4822	0.61399	−2.02422	0.90941
LnGDPpc	567	4.199542	0.49122	2.87947	4.94651
LnGDPpc2	567	17.87703	3.934836	8.291401	24.46803
LnNATR	567	−0.27708	0.84594	−2.06514	1.34283

Table 3
CD test.

Variable	LnCO2	LnNÜK	LnGDPpc	LnGDPpc2	LnNATR
P-value	0.000***	0.631	0.000***	0.000***	0.000***
Group Results					
			LM	**LM_{adj}**	**LM_{CD}**
Statistics			734.2	25.49	8.198
P-value			0.000***	0.000***	0.000***

Here: the signs ***, ** are representing significance at the 1% and the 5% regions.

Table 4
CADF unit root test results.

Variables	Constant		Constant and trend		Decision
	Z(t-bar)	p-value	Z(t-bar)	p-value	
LnCO2	3.345	1.000	2.048	0.980	–
ΔLnCO2	−6.283	0.000***	−4.405	0.000***	I(1)
LnNÜK	1.535	0.938	−1.804	0.036**	I(0)
LnGDPpc	−0.326	0.372	1.979	0.976	–
ΔLnGDPpc	−1.793	0.036**	0.064	0.526	I(1)
LnGDPpc2	−0.365	0.358	2.251	0.988	–
ΔLnGDPpc2	−1.694	0.045**	0.211	0.584	I(1)
LnNATR	0.862	0.806	−0.682	0.248	–
ΔLnNATR	−7.167	0.000***	−5.046	0.000***	I(1)

Note: ***, and ** indicate the significance level at the 1%, and 5% levels, respectively. The lag length is taken as 1.

Table 5
Heterogeneity test results.

Adj.	Delta	p-value
	16.770	0.000***
	19.842	0.000***

Note: ***, and ** indicate the significance level at the 1%, and 5% levels, respectively. Fixed option was used.

4.1. Long-run analysis and causality framework

Table 8 shows the PCSEs estimation results. Broadly speaking, the model has a good fit when examining the statistics of the model in the table. Firstly, the Wald probability value expresses the significance of the model and secondly, the assessed independent variables explain around 85% of the variations in the dependent variable.

From the estimation outcomes, we examined the effects of both nuclear energy utilization and natural resources on the environmental quality of 27 globally dispersed nuclear energy-consuming economies. To begin with the natural resource component of the analysis, it was discovered that resource rents have exposed these economies to more environmental damage as a 1% increase in rents significantly raises carbon emission levels by 0.08%. This finding coincides with some existing literature from different empirical studies showing that natural resources can be harmful to the environment despite their tremendous economic benefits (Dingru et al., 2023; Gyamfi et al., 2023). The aggressive push for economic growth often requires huge energy consumption and a simple examination of the global energy utilization portfolios shows that conventional fossil energy uses disproportionately dominate the global energy consumption chat (BP, 2021). Overall, the natural resources rent mostly accrues from oil rents, natural gas rents, and coal rents, while other mineral rents often account for lesser or sometimes insignificant contributions to the overall rents.

Moreover, when the nuclear energy usage component of the analysis

Table 6
Model selection.

Models	F-Test		Hausman Test		B-P LM Test		Identified Model
	Statics	p-value	Statics	p-value	Statics	p-value	
(Dependent variable lnCO_2)	1560.14	0.000	112.83	0.000	4981.55	0.000	Fixed Effects Model

Table 7
Autocorrelation and heteroskedasticity test.

Wooldridge Test		Modifiye Wald Test	
H_0: No First Order Serial Correlation		H_0: $\sigma_i^2 =$ *for all I* σ^2	
F(1,10)	72.562	**x^2 (11)**	4943.51
p-value > F	0.000	**p-değ< x^2**	0.000

Table 8
Panels corrected standard errors (Pcses) Prediction results.

	Coefficient	Panel-Adjusted Std.Error	p-value
LnNÜK	0.312	0.050	0.000***
LnNATR	0.080	0.020	0.000***
LnGDPpc	−1.089	0.518	0.036**
LnGDPpc2	0.112	0.064	0.081*
Constant	*5.1504*	*1.044*	*0.000****
Model Statistics	*Wald chi2: 43.33* *Prob > chi2: 0.000**** *R^2: 0.85*		

Note: ***, **, * indicate 1%, 5%, and 10% significance level, respectively. Relevant statistics were obtained from the Stata 15 package program.

was examined, it was discovered that nuclear utilization had a harmful effect on the environment, contrary to the environmental benefits expected from this type of energy source, as supported by some empirical studies (Hassan et al., 2020; Sadiq et al., 2023; Kartal et al., 2023). According to the estimates, a 1% increase in nuclear consumption correlates with increased carbon emission by 0.30%. Some plausible explanations could be that, firstly, these nuclear-utilizing nations haven't invested enough in this form of energy generation as argued by (Ulucak and Erdogan, 2022; Duran et. 2022). The current investment amount is not sufficient to achieve the required production level that can significantly compensate for the environmental damage per total fossil energy consumption level to ensure the emission reduction of nuclear energy sources. In addition, although nuclear energy is a low-carbon energy source, there are indirect carbon emissions generated during the construction, operation and fuel cycle processes of nuclear power plants. Although these emissions are very small compared to other energy sources, as seen in Fig. 2, the findings of this study suggest that these indirect emissions may have led to a significant cumulative effect on total emissions. On the other hand, the emissions from fossil utilization may have overshadowed the potential environmental benefits of nuclear utilization. For instance, considering the data on electricity generated over a period of 5 decades, York (2012) demonstrated that every single unit of electricity produced from non-fossil resources (including nuclear) does not even address up to 10% of a single unit of the electricity produces from fossil-fuels. On the other hand, in the study conducted by Ulucak & Erdoğan (2022), they observed that nuclear energy consumption in OECD countries did not reduce carbon emission levels and in this direction, they suggested that these countries should essentially increase their investments for the necessary intensification of nuclear energy.

Overall, the findings are therefore crucial wake-up calls on the other to address the environmental demerits of resource utilization, especially from strategic plans to induce renewable energy consumption and increase the total investments in nuclear energy on the other part. The efforts made to clean energy technological revolution must be sustained. There are many empirical studies that have investigated the effects of environmental technologies on energy transition (Wang et al., 2023; Awosusi et al., 2022; Musah et al., 2024; Alola and Adebayo, 2022; Onifade and Alola, 2022).

The income component of the analysis essentially sheds light on the EKC phenomenon. The result showed that the EKC hypothesis cannot be supported among these nuclear-utilizing economies as an initial one % rise in growth of the economy causes a 1.08% decrease in CO_2 as the environmental quality measure contrary to the EKC submission while a 1% eventual increase in income causes a 1.08% increase in emission. This outcome supports the "U-shape" hypothesis rather than the expected inverted "U" and the results are parallel to the results of Yilanci and Pata (2020) andJozwik (2021). Nevertheless, the findings here support a few existing works in literature like the studies of Koçak (2014), Çalışkan (2022), and kyu Hwang (2022). In essence, it is concluded that successive income growth does not stand to produce desirable environmental benefits among these nuclear-utilizing economies.

The overall findings have been expanded by the causality evidence in

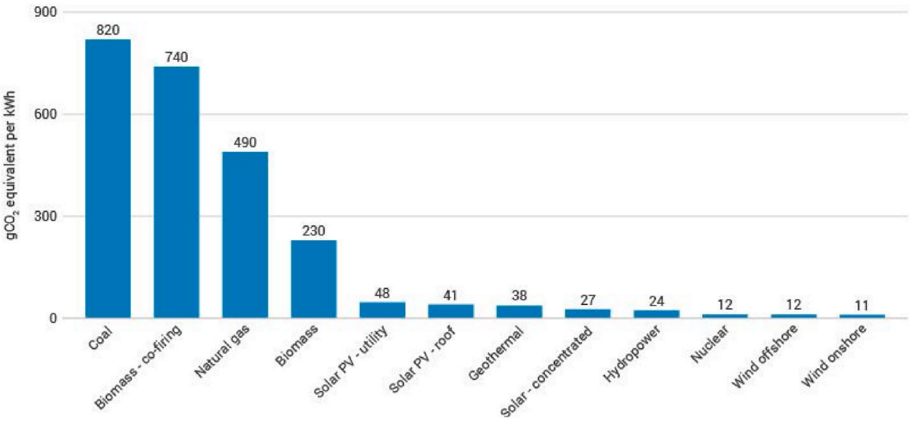


Fig. 2. Average life-cycle carbon dioxide-equivalent emissions for different electricity generators.
Source: Visualization by World Nuclear Organization (WNA, n.d.) using IPCC report

Table 9
Dumitrescu and hurlin heterogeneous panel causality test results.

H_0 *Hypothesis*	For the W-bar	For the Z-bar	The estimated P-value
LnCO2→LnNÜK	2.8365	1.8092	0.004**
LnNÜK→ LnCO2	−0.7461	−0.9947	0.455
H_0 *Hypothesis*	**W-bar**	**Z-bar**	**The estimated P-value**
LnCO2→LnGDPpc	−0.2389	−0.5978	0.8112
LnGDPpc→ LnCO2	2.0501	1.1937	0.0404**
H_0 *Hypothesis*	**For the W-bar**	**For the Z-bar**	**The estimated P-value**
LnCO2→LnNATR	2.6112	1.6328	0.009**
LnNATR→ LnCO2	1.4569	0.7294	0.4657

Note: ***, and ** indicate significance levels at 1% and 5%, respectively. The optimal lag length was determined as 1 according to the information criterion to AIC.

Table 9 based on the Dumitrescu and Hurlin panel causal nexus evaluations. According to the results, the hypothesis that the carbon emission level is not the cause of nuclear energy use was rejected, while the hypothesis that nuclear energy use is not the cause of carbon emission level could not be rejected. Hence the evidence supports a one-way causal relationship running from levels of emission to the amount of nuclear energy use. This shows that the increase in emission levels has granger caused a gradual rise in nuclear utilization among the 27 nuclear energy-utilizing nations. However, the current level of nuclear energy utilization does not produce any significant emission-reduction impact. This is further justifiable as the bulk of energy production especially electricity generation is vastly dominated by fossil energy utilization on a global scale as seen in Fig. 3.

Furthermore, the findings show that there is causality running from economic activities to emissions levels but not the other way around. This implies an uni-directional causality from growth to emissions levels. A unidirectional causality running from the levels of carbon emissions to natural resource rents was also observed among the nuclear energy-utilizing countries.

5. Conclusion and recommendations

Nuclear energy being among the potential non-fossil sources is gaining attention across the globe. Therefore, we examine whether nuclear energy utilization significantly reduces carbon emissions while testing the validity of the EKC among selected nuclear energy-utilizing states. The environmental impacts of natural resource rents were also incorporated into the second-generation empirical analyses that were conducted. A total of twenty-seven (27) globally dispersed nuclear energy-utilizing economies were analyzed. Findings from the coefficient estimator revealed that the EKC hypothesis was not valid in the sample country group. The results also show that neither the levels of nuclear energy use nor the amount of natural resources rent has significantly reduced carbon emissions across the countries. From the coefficient estimator, it is concluded that economic growth, resource rent and nuclear energy use induce carbon emissions. However, considering that nuclear energy is a proven low-carbon energy source, we further scrutinize the results to see if there are significant causality nexuses among these variables and emissions levels. It was discovered that nuclear energy utilization does not significantly granger cause carbon emissions. On the other hand, a one-way causality nexus from emission levels to nuclear energy consumption was discovered. This points to the possibility that the desire to reduce carbon emission levels might have been driving nuclear energy utilization among these countries. However, the current levels of investments in nuclear have not produced significant emission reduction impacts. In addition, there is a one-way causality nexus from income levels to carbon emissions. This finding shows that the right channel of causality is from economic growth to carbon emissions among these 27 nuclear energy-using countries. This suggests that these 27 countries can integrate carbon mitigation policies with minimal economic damage.

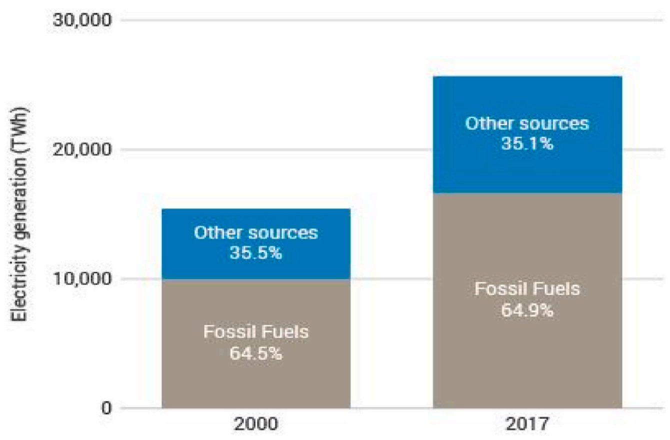


Fig. 3. Fossil versus non-fossil fuel electricity generation in 2000 and 2017. **Source:** Visualization by World Nuclear Organization (WNA, n.d) using IEA World Energy Outlook data

5.1. Policy implications

Following the results, given the environmental detriment of natural resource rents, it is recommended that adequate measures are taken to increase pollution control costs on resource trading companies and organizations. This can be supported by imposing necessary environmental taxes on resource exploitation while ensuring adequate enforcement and compliance. Additionally, these countries can also leverage the resource rents to boost their investments in low-carbon technologies and renewable energy projects so that environmental quality can be improved. In this context, natural resources can be used sustainably, and the environmental impacts of resource exploitation can be minimized.

Considering the emission-inducing impacts of economic growth and the failure to validate the EKC hypothesis, the results suggest that carbon emission levels are largely yet to be decoupled from economic activities among these countries. Economic growth has been linked to energy utilization in the vast literature and fossil energy consumption has dominated economic activities over the years. As such, addressing the current drivers of economic activities and industrial practices would be crucial to attaining environmental sustainability goals among these countries. We recommend that adequate green growth strategies should be put in place such as leveraging public-private partnership schemes to finance green project development among the analyzed countries. It is important for these countries to initiate sustainable development policies and align their individual economic growth strategies with environmental sustainability agendas. As such, all economic growth strategies should be restructured to promote environmental sustainability via investments in clean energy and cleaner production techniques.

Although nuclear energy is a low-carbon energy source, small indirect carbon emissions occur during the construction, operation, and fuel cycle processes of nuclear power plants. Therefore, the results suggest that the indirect harmful environmental effects of nuclear energy use may have cumulatively led to a significant increase in total emissions. Therefore, a two-way strategy would be necessary to maximize the conventional potential environmental benefits of nuclear utilization among these countries. Firstly, we recommend an increase in support for R&D spending on nuclear energy research regarding how to minimize the indirect carbon footprint during the construction, operation, and fuel cycle processes of nuclear power plants. Doing this would not only be beneficial from an environmental perspective but also help to ensure the optimal use of nuclear energy alternatives in the overall energy mix as a more reliable and affordable energy production source. Secondly, following a proper implementation of the first recommendations, the authorities can decisively increase the share of nuclear energy in the overall energy portfolios of these countries. This would help to ensure that environmental degradation from dominant fossil energy utilization does not eventually offset the potential environmental benefits from nuclear energy utilization.

5.2. Limitations and future recommendations

Although the current analysis provided useful insights on whether nuclear energy utilization has significantly driven carbon emission reduction gains among the utilizing states, there are some limitations that provide possible directions for future studies. The period of the study (2000–2020) may not fully reflect current developments and long-term trends beyond this time frame. In addition, major economic crises, and external shocks such as pandemics occurred at the end of this period. Therefore, future studies utilizing a wider data range can examine the effects of such external shocks with tests that take structural breaks into account to ascertain any possible change in the results. Lastly, future studies can also explore other approaches to engage heterogeneity aside from the steps that were taken in this study given that the 27 nuclear energy-utilizing countries have geographical, economic, and political differences.

CRediT authorship contribution statement

Şeyma Bozkaya: Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Stephen Taiwo Onifade:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Conceptualization. **Mahmut Sami Duran:** Validation, Software, Methodology, Investigation, Formal analysis, Data curation.

Ethics approval and consent to participate

NA.

Consent for publication

NA.

Funding

There is no funding received by the author for the study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data for this present study are sourced from the database of the World Development Indicators (WDI, 2021) at: https://data.worldbank.org, and the British petroleum (BP) at (https://www.bp.com)

References

Adams, S., Acheampong, A.O., 2019. Reducing carbon emissions: the role of renewable energy and democracy. J. Clean. Prod. 240, 118245.

Al-Mulali, U., 2014. Investigating the impact of nuclear energy consumption on GDP growth and CO2 emission: a panel data analysis. Prog. Nucl. Energy 73, 172–178.

Al-Mulali, U., Saboori, B., Ozturk, I., 2015. Investigating the environmental Kuznets curve hypothesis in Vietnam. Energy Pol. 76, 123–131.

Alola, A.A., Adebayo, T.S., 2022. Are green resource productivity and environmental technologies the face of environmental sustainability in the Nordic region? Sustain. Dev. 31 (2), 760–772.

Apergis, N., Payne, J.E., 2017. Per capita carbon dioxide emissions across US states by sector and fossil fuel source: evidence from club convergence tests. Energy Econ. 63, 365–372.

Apergis, N., Payne, J.E., 2010. A panel study of nuclear energy consumption and economic growth. Energy Econ. 32 (3), 545–549.

Appiah, M., Li, M., Gyamfi, B.A., 2023. Investigating institutional quality and carbon mitigation drive in Sub-Saharan Africa: are growth levels, energy use, population, and industrialization consequential factors? Energy Environ. 33 (33), 1–14. https://doi.org/10.1177/0958305X221147602, 5.

Awosusi, A.A., Adebayo, T.S., Kirikkaleli, D., Altuntaş, M., 2022. Role of technological innovation and globalization in BRICS economies: policy towards environmental sustainability. Int. J. Sustain. Dev. World Ecol. 29 (7), 593–610.

Aye, G.C., Edoja, P.E., 2017. Effect of economic growth on CO2 emission in developing countries: evidence from a dynamic panel threshold model. Cogent Economics & Finance 5 (1), 1379239.

Baek, J., 2016. Do nuclear and renewable energy improve the environment? Empirical evidence from the United States. Ecol. Indicat. 66, 352–356.

Baek, J., Pride, D., 2014. On the income–nuclear energy–CO2 emissions nexus revisited. Energy Econ. 43, 6–10.

Bandyopadhyay, A., Rej, S., 2021. Can nuclear energy fuel an environmentally sustainable economic growth? Revisiting the EKC hypothesis for India. Environ. Sci. Pollut. Control Ser. 28 (44), 63065–63086.

Beck, N., Katz, J.N., 1995. What to do (and not to do) with time-series cross-section data. Am. Polit. Sci. Rev. 89 (3), 634–647. https://doi.org/10.2307/2082979.

Bozkaya, Ş., Duran, M.S., Awan, A., 2023. Technological innovations in environmental sustainability: a quantitative exploration of their impact on carbon dioxide emissions. Naturel Resources Forum 1–17. https://doi.org/10.1111/1477-8947.12354.

Bozkaya, Ş., Onifade, S.T., Duran, M.S., Kaya, M.G., 2022. Does environmentally friendly energy consumption spur economic progress: empirical evidence from the Nordic countries? Environ. Sci. Pollut. Control Ser. 29 (46), 1–11. https://doi.org/10.1007/s11356-022-23452-4.

Breusch, T.S., ve Pagan, A.R., 1980. The Lagrange multiplier test and its applications to model specification tests in econometrics. Rev. Econ. Stud. 47, 239–253.

Chang, C.C., 2010. A multivariate causality test of carbon dioxide emissions, energy consumption and economic growth in China. Appl. Energy 87 (11), 3533–3537.

Chen, X., Lin, S., Reed, W.R., 2006. Another Look at what to Do with Time-Series Cross-Section Data. Department of Economics, College of Business and Economics, University of Canterbury.

Cakar, N.D., Erdoğan, S., Gedikli, A., Öncü, M.A., 2022. Nuclear energy consumption, nuclear fusion reactors and environmental quality: the case of G7 countries. Nucl. Eng. Technol. 54 (4), 1301–1311.

Çalışkan, U., 2022. The validity of the environmental Kuznets curve hypothesis in eurocontrol as a financial union: an econometric analysis. JOEEP: Journal of Emerging Economies and Policy 7 (1), 305–326.

Danish, K., Ulucak, R., Erdogan, S., 2022. The effect of nuclear energy on the environment in the context of globalization: consumption vs production-based CO2 emissions. Nucl. Eng. Technol. 54 (4), 1312–1320.

Dingru, L., Ramzan, M., AL-Faryan, M.A.S., 2023. Environmental perspectives on the impacts of trade and natural resources on renewable energy utilization in Sub-Sahara Africa: accounting for FDI, income, and urbanization trends. Resour. Pol. 80, 103204. https://doi.org/10.1016/j.resourpol.2022.103204.

Dogan, E., Ozturk, I., 2017. The influence of renewable and non-renewable energy consumption and real income on CO 2 emissions in the USA: evidence from structural break tests. Environ. Sci. Pollut. Control Ser. 24, 10846–10854.

Dumitrescu, E.I., ve Hurlin, C., 2012. Testing for granger non-causality in heterogeneous panels. Econ. Modell. 29 (4), 1450–1460.

Duran, M.S., Bozkaya, Ş., Onifade, S.T., Kaya, M.G., 2022. Nuclear energy consumption and energy-driven growth nexus: a system GMM analysis of 27 nuclear utilizing countries across the globe. Environ. Sci. Pollut. Control Ser. 29 (46), 1–9. https://doi.org/10.1007/s11356-022-22951-8.

Grossman, G.M., Krueger, A.B., 1991. Environmental impacts of a North American free trade agreement. NEER Working Paper. Number: 3914.

Gyamfi, B.A., Adedoyin, F.F., Bein, M.A., Bekun, F.V., 2021. Environmental implications of N-shaped environmental Kuznets curve for E7 countries. Environ. Sci. Pollut. Control Ser. 28, 33072–33082.

Gyamfi, B.A., Taiwo, O.S., Erdoğan, S., Ali, E.B., 2023. Colligating ecological footprint and economic globalization after COP21: insights from agricultural value-added and natural resources rents in the E7 economies. Int. J. Sustain. Dev. World Ecol. 1–15. https://doi.org/10.1080/13504509.2023.2166141.

Hao, Y., 2022. Effect of economic indicators, renewable energy consumption and human development on climate change: an empirical analysis based on panel data of selected countries. Front. Energy Res. 10, 841497.

Hassan, Q., Viktor, P., Al-Musawi, T.J., Ali, B.M., Algburi, S., Alzoubi, H.M., et al., 2024. The renewable energy role in the global energy Transformations. Renewable Energy Focus 48, 100545. https://doi.org/10.1016/j.ref.2024.100545.

Hao, Y., Chen, P., 2023. Do renewable energy consumption and green innovation help to curb CO2 emissions? Evidence from E7 countries. Environ. Sci. Pollut. Control Ser. 30 (8), 21115.

Hoa, Y., Chen, P., Li, X., 2022. Testing the environmental Kuznets curve hypothesis: the dynamic impact of nuclear energy on environmental sustainability in the context of economic globalization. Energy Strategy Rev. 44, 100970.

Hassan, S.T., Baloch, M.A., Tarar, Z.H., 2020. Is nuclear energy a better alternative for mitigating CO2 emissions in BRICS countries? An empirical analysis. Nucl. Eng. Technol. 52 (12), 2969–2974.

Hassan, S.T., Batool, B., Wang, P., Zhu, B., Sadiq, M., 2023. Impact of economic complexity index, globalization, and nuclear energy consumption on ecological footprint: first insights in OECD context. Energy 263, 125628.

Hwang, Y.K., 2022. The energy-growth nexus in 3 Latin American countries on the basis of the EKC framework: in the case of Argentina, Brazil, and Chile. Environ. Sci. Pollut. Res. https://doi.org/10.1007/s11356-022-24360-3.

IAEA, 2018. Climate change and nuclear power. Marketing and Sales Unit, Publishing Section. Vienna, Austria. https://www-pub.iaea.org/MTCD/Publications/PDF/CCNAP-2018_web.pdf.

Inglesi-Lotz, R., Dogan, E., 2018. The role of renewable versus non-renewable energy to the level of CO2 emissions a panel analysis of sub-Saharan Africa's Big 10 electricity generators. Renew. Energy 123, 36–43.

Iwata, H., Okada, K., Samreth, S., 2010. Empirical study on the environmental Kuznets curve for CO2 in France: the role of nuclear energy. Energy Pol. 38, 4057–4063.

Jahanger, A., Hossain, M.R., Onwe, J.C., Ogwu, S.O., Awan, A., Balsalobre-Lorente, D., 2023. Analyzing the N-shaped EKC among top nuclear energy generating nations: a novel dynamic common correlated effects approach. Gondwana Res. 116, 73–88.

Jewell, J., 2011. Ready for nuclear energy? An assessment of capacities and motivations for launching new national nuclear power programs. Energy Pol. 39 (3), 1041–1055.

Jin, T., Kim, J., 2018. What is better for mitigating carbon emissions–Renewable energy or nuclear energy? A panel data analysis. Renew. Sustain. Energy Rev. 91, 464–471.

Jozwik, B., Gavryshkiv, A.-V., Kyophilavong, P., Gruszecki, L.E., 2021. Revisiting the Environmental Kuznets Curve Hypothesis: A Case of Central Europe . Energies 14 (12), 3415. https://doi.org/10.3390/en14123415.

Kartal, M.T., Samour, A., Adebayo, T.S., Depren, S.K., 2023. Do nuclear energy and renewable energy surge environmental quality in the United States? New insights from novel bootstrap Fourier Granger causality in quantiles approach. Prog. Nucl. Energy 155, 104509.

Koçak, E., 2014. Türkiye'de Çevresel Kuznets Eğrisi Hipotezinin Geçerliliği: ARDL Sınır Testi Yaklaşımı. İşletme ve İktisat Çalışmaları Dergisi 2 (3), 62–73.

Kuznets, S., 1955. Economic growth and income inequality. Am. Econ. Rev. 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. Econ. Modell. 77, 12–20.

Li, R., Wang, Q., Li, L., Hu, S., 2023. Do natural resource rent and corruption governance reshape the environmental Kuznets curve for ecological footprint? Evidence from 158 countries. Resour. Pol. 85, 103890.

Lopez, L., Weber, S., 2017. Testing for Granger Causality in Panel Data. University of Neuchatel Institute of Economic Research. IRENE Working paper 17-03.

Menyah, K., Wolde-Rufael, Y., 2010. CO2 emissions, nuclear energy, renewable energy and economic growth in the US. Energy Pol. 38 (6), 2911–2915.

Mkombe, D., Tufa, A.H., Alene, A.D., Manda, J., Feleke, S., Abdoulaye, T., Manyong, V., 2021. The effects of foreign direct investment on youth unemployment in the Southern African Development Community. Dev. South Afr. 38 (6), 863–878.

Moundigbaye, M., Rea, W.S., Reed, W.R., 2018. Which panel data estimator should I use?: a corrigendum and extension. Economics 12 (1).

Musah, M., Onifade, S.T., Ankrah, I., Gyamfi, B.A., Amoako, G.K., 2024. Achieving net-zero emission target in Africa: are sustainable energy innovations and financialization crucial for environmental sustainability of sub-Saharan African state? Appl. Energy 364, 123120. https://doi.org/10.1016/j.apenergy.2024.123120.

Naimoğlu, M., 2022. The impact of nuclear energy use, energy prices and energy imports on CO2 emissions:Evidence from energy importer emerging economies which use nuclear energy. J. Clean. Prod. 373, 133937.

Oluwatobi, A.A., Daniel, G.A., Akande, J.O., 2022. On export and economic growth: a comparative analysis of selected West African countries. Int. J. Econ. Financ. Issues 12 (4), 106–113.

Onifade, S.T., Alola, A.A., 2022. Energy transition and environmental quality prospects in leading emerging economies: the role of environmental-related technological innovation. Sustain. Dev. 30 (2), 1–13. https://doi.org/10.1002/sd.2346.

Onifade, S.T., 2022. Retrospecting on resource abundance in leading oil-producing African countries: how valid is the environmental Kuznets curve (EKC) hypothesis in a sectoral composition framework? Environmental Science and Pollution Research. Environ. Sci. Pollut. Control Ser. 29 (1), 52761–52774. https://doi.org/10.1007/s11356-022-19575-3.

Onifade, S.T., Alola, A.A., 2023. Environmental quality outlook of the leading oil producers and urbanized African states. Environ. Sci. Pollut. Control Ser. 30 (43), 98288–98299. https://doi.org/10.1007/s11356-023-28915-w.

Onifade, S.T., 2023. Environmental impacts of energy indicators on ecological footprints of oil-exporting African countries: perspectives on fossil resources abundance amidst sustainable development quests. Resour. Pol. 82, 103481. https://doi.org/10.1016/j.resourpol.2023.103481.

Ozturk, I., 2017. Measuring the impact of alternative and nuclear energy consumption, carbon dioxide emissions and oil rents on specific growth factors in the panel of Latin American countries. Prog. Nucl. Energy 100, 71–81.

Pata, U.K., Kartal, M.T., 2022. Impact of nuclear and renewable energy sources on environment quality: testing the EKC and LCC hypotheses for South Korea. Nucl. Eng. 55 (2), 587–594.

Pesaran, M.H., 2004. General diagnostic tests for cross section dependence in panels. Cambridge Working Papers in Economics, p. 435.

Pilatowska, M., Geise, A., Włodarczyk, A., 2020. The effect of renewable and nuclear energy consumption on decoupling economic growth from CO2 emissions in Spain. Energies 13 (9), 2124.

Sadiq, M., Shinwari, R., Wen, F., Usman, M., Hassan, S.T., Taghizadeh-Hesary, F., 2023. Do globalization and nuclear energy intensify the environmental costs in top nuclear energy-consuming countries? Prog. Nucl. Energy 156, 104533.

Sadorsky, P., 2011. Trade and energy consumption in the Middle East. Energy Econ. 33 (5), 739–749.

Saidi, K., Omri, A., 2020. Reducing CO2 emissions in OECD countries: do renewable and nuclear energy matter? Prog. Nucl. Energy 126, 103425.

Sarkodie, S.A., Adams, S., 2018. Renewable energy, nuclear energy, and environmental pollution: accounting for political institutional quality in South Africa. Science of the total environment 643, 1590–1601.

Sharif, A., Bhattacharya, M., Afshan, S., Shahbaz, M., 2021. Disaggregated renewable energy sources in mitigating CO2 emissions: new evidence from the USA using quantile regressions. Environ. Sci. Pollut. Control Ser. 28 (41), 57582–57601.

Tsimisaraka, R.S.M., Xiang, L., Andrianarivo, A.R.N.A., Josoa, E.Z., Khan, N., Hanif, M.S., et al., 2023. Impact of financial inclusion, globalization, renewable energy, ICT, and economic growth on CO2 emission in OBOR countries. Sustainability 15 (8), 6534.

Ulucak, R., Erdogan, S., 2022. The effect of nuclear energy on the environment in the context of globalization: consumption vs production-based CO2 emissions. Nucl. Eng. Technol. 54 (4), 1312–1320.

Usman, M., Kousar, R., Makhdum, M.S.A., Yaseen, M.R., Nadeem, A.M., 2022. Do financial development, economic growth, energy consumption, and trade openness contribute to increase carbon emission in Pakistan? An insight based on ARDL bound testing approach. Environ. Dev. Sustain. 1–30.

Wang, Q., Guo, J., Li, R., Jiang, X.T., 2023. Exploring the role of nuclear energy in the energy transition:A comparative perspective of the effects of coal, oil, natural gas, renewable energy, and nuclear power on economic growth and carbon emissions. Environ. Res. 221, 115290.

WNA (n.d). World Nuclear Association. How can nuclear combat climate change? Available at: https://world-nuclear.org/nuclear-essentials/how-can-nuclear-combat-climate-change#:~:text=Nuclear%20power%20plants%20produce%20no,electricity%20when%20compared%20with%20solar. Accessesd 2nd September 2024.

World Nuclear Association, 2022. World Nuclear Performance Report 2022. Report No. 2022.

Yilanci, V., Pata, U.K., 2020. Investigating the EKC hypothesis for China: the role of economic complexity on ecological footprint. Environ. Sci. Pollut. Res. 27, 32683–32694.

York, R., 2012. Do alternative energy sources displace fossil fuels? Nat. Clim. Change 2 (6), 441–443.

Zahariadis, N., Exadaktylos, T., Sparf, J., Petridou, E., Kyriakidis, A., Papadopoulos, I., 2022. Assessing the effectiveness of public health interventions for Covid-19 in Greece and Cyprus. European policy analysis 8 (3), 345–359.

Zhang, J., Ali, S., Ping, L., 2023. Asymmetric linkages between nuclear energy and environmental quality:Evidence from Top-10 nuclear energy consumer countries. Nucl. Eng. Technol. 55 (5), 1878–1884.