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Does nuclear energy mitigate CO_2 emissions in the USA? Testing IPAT and EKC hypotheses using dynamic ARDL simulations approach

Abubakar Hassan [a], Mohammad Haseeb [b], Festus Victor Bekun [c,d,e], Asieh Haieri Yazdi [f], Ehsan Ullah [g], Md. Emran Hossain [h,*]

[a] *Economics Studies, School of Business, University of Dundee, United Kingdom*
[b] *School of Economics and Management, and Center for Industrial Economics, Wuhan University, Wuhan 430072, China*
[c] *Faculty of Economics Administrative and Social Sciences, Istanbul Gelisim University, Istanbul, Turkey*
[d] *Research Center of Development Economics, Azerbaijan State University of Economics (UNEC), Istiqlaliyyat Str. 6, Baku 1001, Azerbaijan*
[e] *Adnan Kassar School of Business, Department of Economics, Lebanese American University, Beirut, Lebanon*
[f] *Centre for Energy, Petroleum, and Minerals Law and Policy, University of Dundee, Scotland, United Kingdom*
[g] *Graduate School of Economics and Management, Ural Federal University, Yekaterinburg, Russia*
[h] *Department of Agricultural Sciences, Texas State University, San Marcos, TX 78666, USA*

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ABSTRACT

Growing concern over climate change mitigation has heightened the search for low-carbon, affordable, and non-intermittent energy alternatives. In this perspective, hydropower, thermal, solar, photovoltaic, and nuclear energy sources fit all these qualities as they are well-known as cleaner and ecosystem-friendly energy sources. However, despite the attractiveness of the clean energy transition, the extant literature has less documentation on the pertinent role of nuclear energy in the "climate change mitigation (SDG-13)" agenda, hence making it difficult to predict nuclear energy-CO_2 emissions (CO_2e) nexus. Hence, the present study, using IPAT and the "environmental Kuznets curve (EKC)" framework, explores the consequences of nuclear energy generation, population dynamics, and economic progress on CO_2e in the "United States of America (USA)" by applying a "dynamic autoregressive distributed lag (DARDL)" model from 1973 to 2021. The study provides evidence the existence of the EKC phenomena, suggesting that economic expansion hurts the environment up to a specific threshold level of per capita income, which is identified as US$ 29,581.16. Further empirical findings also show the detrimental effect of population-induced-emission. Remarkably, a 1% rise in nuclear energy generation dwindles CO_2e by around 0.819%. The outcomes of this research demonstrate that economic growth level, population, and CO_2 emission are entangled. However, there is a need for a collective role from both stakeholders and policymakers in achieving "SDG-13" as well as "clean and affordable energy (SDG-7)" with a paradigm shift of the USA energy portfolio away from fossil fuels to renewables.

1. Introduction

In the last decades, climate change has emerged as a key concern that several countries must contend with (Lee et al., 2022). This issue has incited policymakers to seek ecologically conducive energy sources capable of fulfilling their energy requirements while simultaneously curbing CO_2e to achieve net-zero targets (Danish et al., 2022; Yahya and Lee, 2023; Lee et al., 2023a). In this regard, the primary strategy is to actively encourage the utilization of renewable and nuclear energy sources in the energy basket as a means to reduce CO_2e (Pata and Samour, 2022). In addition, as the climate crisis has grown more dire and fossil fuels have become scarcer, nuclear energy has been put out as a safe, secure, affordable, carbon-free answer to energy and climate issues (Brook et al., 2014; Duscha et al., 2014). Nuclear energy is seen as a significant means of limiting global temperature to levels below 2 °C (IEA, 2021). The establishment of energy security inside a nation serves as a fundamental basis for the utilization of nuclear power to diversify energy supplies and address the pressing issue of climate change. Nevertheless, there is a lack of consensus on the global stage about nuclear energy and climate change mitigation actions. Thus, this study

* Corresponding author.
E-mail addresses: ahassan001@dundee.ac.uk (A. Hassan), haseeb.ecb@gmail.com (M. Haseeb), fbekun@gelisim.edu.tr (F.V. Bekun), 2391480@dundee.ac.uk (A. Haieri Yazdi), ehsanmiani@gmail.com (E. Ullah), emranaerd@gmail.com (Md.E. Hossain).

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has attempted to address the following queries and examine this approach: Is nuclear energy a viable energy source in the USA that can help reduce climate change effects?

The interrelationship among "nuclear energy use, CO_2e, and economic development" has been the subject of contemporary scholarly discourse in the field of economics. There exists a strong connection between the "utilization of nuclear energy and CO_2e, as well as between economic development and CO_2e" (Saidi and Mbarek, 2016). However, there exists a significant apprehension over the environmental problem due to the potential correlation between energy consumption and economic expansion, which serves as the primary catalyst for environmental degradation. Yet, given the predominant reliance on fossil fuels for present power generation, it is anticipated that the proliferation of nuclear energy-based production methods would have a substantial impact on mitigating CO_2e (Hoffert et al., 2002). This is because nuclear energy is regarded as a viable solution to address the issue of escalating oil costs and mitigating reliance on other nations for energy resources. In addition, it is worth noting that nuclear energy has effectively fulfilled the global energy requirements in some regions characterized by rapid expansion in energy consumption, the imminent depletion of oil and gas supplies within a few generations, and the crucial need to mitigate greenhouse gas emissions (Toth and Rogner, 2006).

Numerous nations have constructed nuclear power plants as part of their strategic efforts to enhance energy security. This approach serves multiple purposes, including diminishing reliance on oil imports, extending the availability of reliable energy sources, mitigating the adverse effects of price fluctuations associated with oil imports, and mitigating emissions (Vaillancourt et al., 2008). In this context, as the world's biggest nuclear energy producer (WNA, 2020), the USA is planning to promote the most ambitious policy in the energy-environmental pollution nexus, called the "zero-emission credit" (ZEC) program through using nuclear power. The "USA Nuclear Energy Institute" claims to provide "reliable baseload electricity without carbon emissions or other air pollution (NEI, 2018)". The ZEC program provides incentives to assist nuclear power plants and prevent them from enclosure because of the relatively low-price wholesale electric market in the USA (EIA, 2019).

Given the significance of nuclear power, it can be stated that the Paris Accord, which was ratified in 2015 and went into effect in 2016, has a unique position in the advancement of nuclear energy for the protection of the environment. This agreement acknowledges that nuclear energy, a low-carbon technology with a track record of success, plays a major role in helping the Paris Agreement meet its climate change target (Prăvălie and Bandoc, 2018). The objective of this initiative is to increase the proportion of nuclear energy in global electricity generation to 25% by the year 2050 (Sarkodie and Adams, 2018). Consequently, nuclear energy plays a substantial role in electricity generation due to its capacity to minimize carbon emissions, particularly in developed countries such as the USA.

Despite being acknowledged as a low-carbon energy source, nuclear power frequently takes centre stage in debates about energy and climate policy (WNA, 2020). This is partly because the issues raised by the use and development of nuclear power are incredibly complex, multidimensional, and even controversial (Danish et al., 2021a). Some of the concerns include nuclear waste disposal and inter-generational equity, nuclear weapons proliferation, radiation, safety and human health, technology choice, public support for large-scale, and capital-intensive investments with long lifetimes (Abbott, 2011; Davis, 2012; Pickard, 2010). Upon weighing advantages and disadvantages, it seems certain that nuclear energy will always hold a special place in a nation's energy mix. Based on the preceding discussion, this study aims to investigate the influence of nuclear energy on environmental sustainability within the framework of "Impact, Population, Affluence, and Technology (IPAT)" and verify the hypothesis of the "environmental Kuznets curve (EKC)" specifically for the USA. The anticipated outcome of this research is to offer novel perspectives that can inform policymakers.

This study makes three significant contributions: Firstly, to date, there exists a dearth of scholarly investigations that have specifically examined the impact of nuclear energy on the IPAT-EKC hypothesis in the USA, given the USA's prominent position in addressing the climate change agenda. The USA warrants particular attention in the study due to its status as a highly industrialized nation that consumes a significant quantity of natural resources, hence exerting tremendous environmental pressure. Consequently, the USA is positioned as the second largest emitter of CO_2. The USA now possesses 93 operational commercial nuclear reactors distributed among 54 nuclear power facilities situated in 28 states (EIA, 2023). This data suggests that the USA has significant capacity to contribute to its energy portfolio through the utilization of nuclear power. Hence, the implementation of a well-crafted and prudent nuclear energy policy by the USA has the potential to effectively address its air pollution predicament in the foreseeable future. Secondly, apart from analyzing the connection between nuclear power and environmental damage, this research also explores the soundness of the standard EKC hypothesis". The EKC theory proposes a curvilinear association between pollution and income, characterized by an "inverted U-shaped" pattern, particularly in the context of nuclear energy contexts. Thirdly, in contrast to existing research, this analysis employs a recently established econometric methodology known as "dynamic autoregressive distributed lag (DARDL) simulation". This technique is utilized within the framework of the extended EKC and IPAT models, incorporating the inclusion of nuclear energy. This methodology acquires, stimulates, and automatically generates plots of deceptive change in regressand based on the regressor while controlling for other variables. Additionally, this approach aids in reducing the complexity and ambiguity associated with the current ARDL paradigm.

The subsequent sections of the article are structured in the following manner. The present literature review encompasses a comprehensive analysis of scholarly research that has investigated the impact of nuclear energy on CO_2e, employing the EKC with the IPAT models as theoretical frameworks. Next, in the "data and methodology section," data sources and methods of analysis are described. The "results and discussion section" presents analyses, and discusses the findings of the research article. Ultimately, after analyzing and deliberating over the findings, the paper finishes the study by providing policy suggestions and offering potential avenues for future research endeavors.

2. Literature review

Proponents of nuclear power have strategically positioned it as a crucial approach to address the challenges posed by climate change and mitigate greenhouse gas (GHG) emissions (Kargari and Mastouri, 2011). Consequently, several academics have conducted research on the impact of economic growth and the creation of nuclear power on the preservation of the environment. Most studies demonstrate a negative link between the generation of nuclear power and CO_2e, indicating that increasing nuclear energy lowers CO_2e (Iwata et al., 2010, 2011; Baek and Kim, 2013).

Using data from the USA from 1960 to 2007 and a modified version of the "Granger causality" test, Menyah and Wolde-Rufael (2010) speculated that nuclear power can assist in reducing CO_2e. Similarly, Baek and Pride (2014) used the "multivariate cointegrated vector autoregression (CVAR)" approach to articulate the income-nuclear energy-CO_2e relationship in the "USA, France, Japan, Korea, Canada, and Spain". The results of the study provided empirical evidence in favor of the notion that nuclear energy contributes to the reduction of CO_2e in nations characterized by significant nuclear power generation. However, it is worth noting that this trend does not hold true for Spain. For the period 1995–2015, Lau et al. (2019) looked at the effects of electricity production from nuclear sources on CO_2e in 18 OECD countries, which included the USA. They used the "panel dynamic Generalized Method of Moments (GMM)" and the panel "Fully Modified Ordinary Least Squares (FMOLS)" approach. The investigation confirmed that in the selected

OECD countries, including the USA, the generation of power from nuclear sources leads to a decrease in CO_2e. According to Murshed et al. (2022), the G7 bloc's usage of nuclear energy reduces CO_2e.

Several other studies also reported the same outcomes for the USA in panel studies. Kim (2021) reported that nuclear power generation helps cut CO_2e in the sixteen biggest nuclear power-producing nations: "the USA, France, Japan, South Korea, Canada, Sweden, the UK, Spain, India, Belgium, Switzerland, Finland, Bulgaria, Argentina, Pakistan, and the Netherlands". Pan et al. (2022) conducted a study utilizing a quarterly dataset spanning from 1990 to 2019 to examine the influence of nuclear energy on CO_2e in the leading nations that consume nuclear power. The "quantile-on-quantile (QQ) estimator" and "Granger causality in quantiles" techniques were used in the investigation. The results of the QQ estimator showed that nuclear power leads to less ecological damage in the "USA, France, Russia, South Korea, Canada, Ukraine, Germany, and Sweden" in most of the quantiles. Anser et al. (2021) also revealed comparable outcomes for the USA after analysing the data from the selected ninety nations. The "Driscoll-Kraay regression" method was used by Danish et al. (2022), who discovered that the utilization of nuclear energy contributes to the mitigation of CO_2e resulting from industry activities in OECD countries.

On the contrary, an alternative body of research has shown that nuclear power either releases CO_2 or exerts a negligible direct impact on environmental degradation. For instance, nuclear energy has no influence on carbon emissions in the long term in 30 countries including the USA (Jin and Kim, 2018). Jaforullah and King (2015) used the "VECM framework" to demonstrate that expanding nuclear energy usage is futile in reducing CO_2e for the USA. Nuclear energy, according to Nathaniel et al. (2021), significantly lowers CO_2e in all G7 nations, except for Canada and the USA.

Since the commencement of the debate between economic development and emissions, many researchers have argued about whether technology can assist in lessening the growth-emission nexus (Lee and Hussain, 2023; Wen et al., 2023; Lee et al., 2023b). A significant portion of the discourse has been centered around the IPAT identity, which serves as a framework for discerning the various elements that influence environmental quality. The IPAT framework is made up of three essential elements: "population (P), affluence (A), and technology (T)". Several past studies used the IPAT framework to investigate whether excessive population size is a burden or a blessing for the environment. However, only a very limited number of studies were carried out in the USA utilizing the IPAT paradigm. Koçak and Ulucak (2019) discovered that the urban population had a favourable impact on CO_2e in 19 high-income OECD nations, including the USA using the extended STIRPAT model. Tian and Da Costa (2013) also used an IPAT technique. To investigate the degree of spatial variability in the mechanism that ties total CO_2e, Videras (2014) employed US county-level data using the STRIPAT framework.

In the available literature, there is a voluminous study on the EKC. Essentially, the EKC arose from Kuznets' (1955) initial study, which suggested that "as per capita income rises, income disparity rises first and then falls". Numerous scholarly investigations have been conducted to examine the veracity of the EKC theory since "Grossman and Krueger (1991)" pioneering study. The EKC concept has also been the focus of several researches conducted in the USA, whether considering a panel of countries, national studies, or investigations at the state level data. Apergis et al. (2017) discovered that 10 out of the 48 USA states support the EKC hypothesis. Aslan et al. (2018) used "bootstrap window estimation" to validate the EKC hypothesis. Bulut (2019) employed the "Gregory Hansen cointegration" test to discover an "inverted U-shaped" relationship between industrial production and CO_2e. Using the "common correlated effects estimator" for the years 1980–2015, Işık et al. (2019) discovered that the EKC concept holds true in 5 out of 10 USA states. The combined cointegration test was used by Pata (2021) for the years 1980 through 2016. The study's key finding is that for the USA, the "inverted U-shaped EKC" still holds true. A similar conclusion was also drawn by Alola and Ozturk (2021). In addition, Nathaniel et al. (2021) for G7 nations, are among the other noteworthy studies that validate the EKC theory in the USA.

However, some research has shown that the EKC concept is erroneous in the USA. For instance, using "an ARDL model", Dogan and Turkekul (2016) reported that the EKC for the USA is not endorsed by this study because actual output improves the environment. Using the "bound testing method" and the "Gregory-Hansen cointegration" test, Dogan and Ozturk (2017) demonstrated that the EKC is invalid in the USA. Shahbaz et al. (2017) employed a bounds test with a structural break that contradicts the EKC hypothesis and discovered an "N-shaped association between CO_2e and income level". Tzeremes (2018) used a "time-varying vector autoregressive model" to find an "N-shaped relationship between income level and CO_2e" in most of the 50 USA states. Using a "dynamic ARDL model", Aslan et al. (2022) considered the emission from various sub-sectors over the years 1972–2020. Except for one mode where total CO_2 emission is the response variable, they found no findings in any model that supported the EKC hypothesis.

2.1. Literature gap

Unlike prior studies on the IPAT framework, this study adds some unique insights. To begin with, the GDP and population size have been extensively researched in the IPAT concept due to their critical roles in carbon dioxide emissions; however, very few research were conducted considering the IPAT framework to explain CO_2e in the USA. Second, several studies in the past have disregarded the IPAT concept when investigating the impact of nuclear energy on CO_2e (Danish et al., 2021b), with no exception for the USA. Third, the current study also draws motivation from the EKC phenomenon for its theoretical backing. However, in the extant literature, there is no consensus on empirical outcomes in terms of the EKC in the USA, which demands further analysis using a robust econometric method.

3. Data and methodology

3.1. Data

This research utilizes yearly time series data of the USA's total "carbon dioxide emissions (CO_2e) measured in metric tons per capita", "Gross Domestic Product (GDP), measured in millions of US dollars per person", "US population (POP) in a total number of people living in the USA (in thousands)", and "total nuclear electricity net generation (NEG) measured in millions of kilowatt-hours", for 1973 to 2021. The CO_{2e} and nuclear electricity net generation datasets are sourced from the "U.S. Energy Information Administration (EIA) monthly energy review", while the population statistics and GDP per capita data are retrieved from the "World Bank's World Development Indicators (WDI)". We use the natural logarithm of all variables under consideration to address the difficulties of heteroscedasticity and data sharpness (Paramati et al., 2017). Besides, the time series plot of the factors of interest in the present investigation is depicted in Fig. 1.

3.2. Theoretical background and model specifications

This study is grounded in two theoretical frameworks, namely the "Environmental Kuznets Curve (EKC)" hypothesis and the "Impact-Population-Affluence-Technology (IPAT)" paradigm. The EKC framework has been widely utilized to assess the influence of economic expansion on ecological quality. The EKC framework depicts a curvilinear relationship between pollution levels and per capita income, characterized by an inverted U-shaped pattern. The impact of economic growth on environmental sustainability may be elucidated through three distinct perspectives under the EKC framework, as proposed by Grossman and Krueger (1991). The EKC paradigm posits that the early stages of economic growth contribute to an increase in CO_2e.

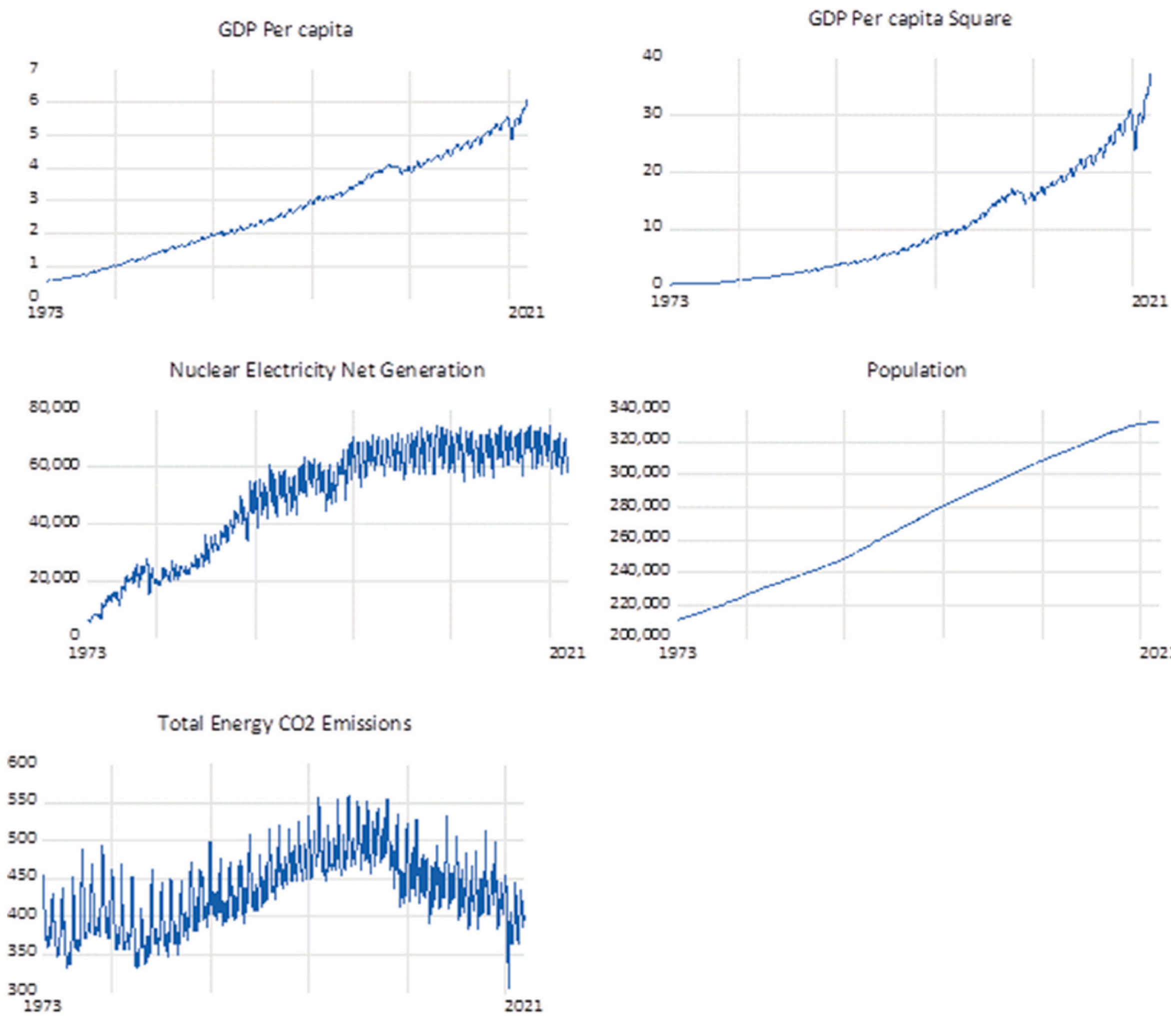

Fig. 1. The trend of studied variables.

Consequently, a trade-off between economic development and ecological pollution is anticipated during this first period of economic growth (Sadorsky, 2010). During the premature stages of economy, the implementation of economic development initiatives may result in an escalation of ecological pollution, which may be attributed to the scale impact of economic development (Murshed and Dao, 2022). During the subsequent stage, the progression of economic growth will precipitate a shift from energy-intensive manufacturing processes to the expansion of ecologically sustainable service sectors. Over time, there is a transition observed in the economy towards sectors that primarily focus on information-based services and businesses that exhibit lower levels of carbon emissions. The phenomenon under consideration is the trajectory of economic expansion influence, often referred to as the composite and technique effect which shows that when income levels rise, there is a corresponding drop in emissions (Kaika and Zervas, 2013). The EKC framework is depicted in Fig. 2.

Many studies have been greatly interested in the interlocking relationships between population growth, resource endowments, and the environment (Ehrlich and Holdren, 1971). Ehrlich & Holdren developed a model when investigating "the environmental impact (I) of the United States's population (P), affluence (A), and technology (T) on carbon emissions", and this model later came to be known as the IPAT framework. We used nuclear energy as a proxy for technology in this study because it is regarded as high-tech (Fan and Watanabe, 2006), and its uses are limited to a handful of developed and developing countries due to its high cost as well as required advanced technology in the generation of energy (Meng and Yu, 2018). According to Danish et al. (2021b), nuclear energy has the potential to serve as a means of showcasing technological advancements inside a nation due to its reliance on sophisticated technological processes.

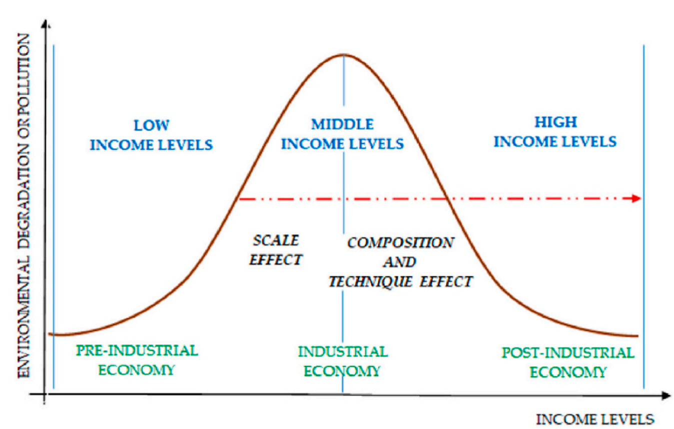

Fig. 2. Depiction of EKC hypothesis.

The primary objective of this study is to examine the environmental ramifications of the "population in thousands of people (POP), affluence proxied by GDP per capita income (GDP), and technology proxied by nuclear electricity net generation (NEG) on carbon emissions (CO_2)" in the USA using the IPAT model on the ground of EKC idea in the USA. Therefore, the following IPAT-EKC model is formulated, as recently done by Danish et al. (2021b).

Taking the natural logarithm of all the variables, Eq. (1) is transformed into a double-logged mathematical model as follows:

$$lnCO_{2t} = \alpha_0 + \alpha_1 \ ln \ GDP_t + \alpha_2 \ ln \ GDP_t^2 + \alpha_3 \ ln \ POP_t + \alpha_4 \ ln \ NEG_t \quad (2)$$

$$\Delta(\ln CO_2)_t = \alpha_0 + \alpha_1 \ln CO_{2t-1} + \alpha_2 \ln GDP_{t-1} + \alpha_3 \ln GDP_{t-1}^2 + \alpha_4 \ln POP_{t-1} + \alpha_5 \ln NEG_{t-1} + \sum_{i=1}^{p} \beta_1 \Delta \ln CO_{2t-i} + \sum_{i=1}^{p} \beta_2 \Delta \ln GDP_{t-i} + + \sum_{i=1}^{p} \beta_3 \Delta \ln GDP_{t-i}^2 + \sum_{i=1}^{p} \beta_4 \Delta \ln POP_{t-i} + \sum_{i=1}^{p} \beta_5 \Delta \ln NEG_{t-i} + u_t \quad (4)$$

Theoretically, it is expected that α_1 and α_2 to carry negative and positive signs, respectively, if the EKC hypothesis holds, α_3 can be negative since higher population density may result in an adverse consequence on the environment or positive due to the positive impact of higher population pressures on competition and technological innovations may improve the quality of the environment, while α_4 can be negative since nuclear electricity generation is a low-carbon technology and consider as an alternative for fossil fuels energy. Thus, it is regarded as a clean source of electricity in nature, and its impact on environmental quality is claimed to be positive. Eq. (2) can be further developed into an econometric form as:

$$lnCO_{2t} = \alpha_0 + \alpha_1 \ ln \ GDP_t + \alpha_2 \ ln \ GDP_t^2 + \alpha_3 \ ln \ POP_t + \alpha_4 \ ln \ NEG_t + \mu_t \quad (3)$$

Where $\ln CO_2$, lnPOP, and lnNEG indicate the natural logarithm of carbon dioxide emissions, total population, and nuclear energy generation, while lnGDP and $\ln GDP^2$ are the natural logarithms of GDP per capita and square of GDP per capita. In addition, μ_t represents error terms assumed to be “normal, identically, and independently distributed around zero mean and constant variances”. It is included in the model to consider the impact of random noise resulting from the error of measurements and or from the unintentional omission of important variables.

3.3. Econometric model specifications

Before utilizing econometric approaches, we conducted stationarity or unit root testing. We utilized the “Augmented Dickey-Fuller (ADF) (Dickey and Fuller, 1979)” and “Phillips-Perron (PP) (Phillips and Perron, 1988)” tests to assess the data’s stationarity characteristics whether integrated at I(0) or I(1).

Before employing the “dynamic ARDL” technique, cointegration testing is required to ensure that the researched variables have a long-term connection. To do so, we must first use the “ARDL bounds test” to demonstrate a long-run link between the variables in Equation (3). “The ARDL F-bounds test’s null hypothesis is that no variables cointegrate (H_0: $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = 0$). The alternative hypothesis (H_1: $\alpha_1 \neq \alpha_2 \neq = \alpha_3 \neq \alpha_4 \neq 0$), on the other hand, defines the presence of cointegration”. “The long-run relationship may be found if the F-statistic value surpasses the crucial values. If the lower limit value exceeds the expected F-statistics, there is no long-term relationship between the variables. The conclusion is inconclusive if the calculated F-statistics are in the midway of the upper and lower bounds (Pesaran et al., 2001).” The following ARDL bounds test equation presented aims to evaluate the long-term association between the specified variables, relying on the assumptions of cointegration:

where t-i defines the optimal lags selected considering the “Akaike information criterion (AIC)”, p signifies lag length, and u_t indicates error term. Furthermore, the expression of the long-term relationship between the variables under investigation is demonstrated by α.

Given the main objective of this study, a DARDL model recently introduced by “Jordan and Philips (2018)” is deployed as the estimation technique due to its advantages over the traditional ARDL model. The DARDL model uses a versatile method that enables the simulation of many ARDL models (Bello and Ch’ng, 2022). The dynamic methodology employs counterfactual scenarios to capture the main findings, as opposed to the hypothesis testing of estimated parameters conducted by the standard ARDL method. In addition, the DARDL model employs a graphical representation to predict counterfactual variations and account for the varying magnitudes of effects associated with a single explanatory variable, while holding the impacts of all other factors on the dependent variable constant (Jordan and Philips, 2018). The present work utilized the “dynamic ARDL error correction term” to estimate the parameters vector, which was drawn from a multivariate normal distribution. The estimation process involved conducting 5000 simulations. Based on the prior studies conducted by Jordan and Philips (2018), Sarkodie et al. (2019), Abbasi et al. (2021), and Abbasi et al. (2022), it is possible to convert Equation (3) into a dynamic ARDL error correction model, which may be represented as follows:

$$\Delta \ln(CO_2)_t = \lambda_0 + \theta_1 lnCO_{2t-1} + \theta_2 \ ln \ GDP_{t-1} + \theta_3 \ ln \ GDP_{t-1}^2 + \theta_4 \ ln \ POP_{t-1} + \theta_5 \ ln \ NEG_{t-1} + \vartheta_1 \Delta lnCO_{2t-1} + \vartheta_2 \Delta ln \ GDP_{t-1} + \vartheta_3 \Delta ln \ GDP_{t-1}^2 + \vartheta_4 \Delta ln \ POP_{t-1} + \vartheta_5 \Delta ln \ NEG_{t-1} + \xi ECT_{t-1} + \mu_t \quad (5)$$

The successful implementation of this methodology hinges on the establishment of cointegration among the variables through bound testing, as well as the requirement that the dependent variable possesses a strictly integrated order of 1. In contrast, the remaining series may exhibit mixed integrating orders of 1 and 0 (Jordan and Philips, 2018). Furthermore, this study employs many diagnostic tests such as “CUSUM and CUSUMSQ”. The “Breusch-Godfrey Lagrange Multiplier (LM)" test was employed to detect the presence of serial correlation, whilst the “Jarque-Bera test” was employed to verify the assumption of normality. The “Breusch-Pagan-Godfrey” tests were employed to detect heteroscedasticity. Ultimately, the “Ramsey reset” test was employed to assess the adequacy of the model’s presentation. Moreover, the “conventional

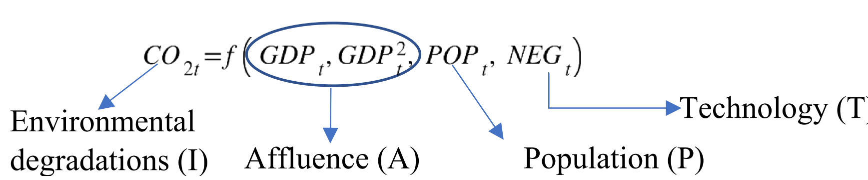

Table 1
"Summary statistics and correlation matrix of studied variables".

	CO_2	GDP	GDP^2	NEG	POP
Mean	18.897	43,845.7	2.03e+09	48,821.15	271,024.1
Median	19.267	43,540.71	1.90e+09	56,129.33	271,025.5
Max.	22.510	60,836.77	3.70e+09	67,451	329,484.1
Min.	14.805	27,363	7.49e+08	6956.5	211,909
Std. Dev.	1.952	10,404.68	9.09e+08	19,613.45	37,510.02
Skewness	−0.492	−0.065	0.1579	−0.714	0.019
Kurtosis	2.473	1.637	1.669	2.014	1.643
Observations	48	48	48	48	48
Correlation matrix					
CO_2	1.000				
GDP	0.763	1.000			
GDP^2	0.780	0.855	1.000		
NEG	−0.659	0.7466	0.714	1.000	
POP	0.810	0.823	0.831	0.733	1.000

ARDL" model was employed to evaluate the reliability of the findings obtained from the "dynamic ARDL" analysis.

4. Results and discussion

Table 1 presents the findings of the statistical analyses and the matrix of correlation analysis. The findings unequivocally demonstrate that, among the chosen variables, CO_2 displays the least amount of fluctuation across all data points owing to its comparatively low standard deviation. Conversely, population (POP) demonstrates the highest level of volatility across all data points due to its substantial standard deviation. The examination of skewness and kurtosis provides more evidence to refute the assumption of normal distribution for the variables. Moreover, the results pertaining to skewness indicate that the variables CO_2, GDP, and NEG exhibit a leftward skewness, whereas GDP2 and POP display a rightward skewness. Table 1 presents the correlation matrix of the variables, indicating the absence of any issues related to multicollinearity. This prerequisite is essential for proceeding with the regression analysis.

The outcomes of the unit root tests are presented in Table 2, employing the conventional ADF and PP tests for this examination. Table 2 presents the results indicating that all of the chosen variables exhibit non-stationarity at the level, as determined by the "Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests". Following the first differences, the selected variables exhibit stationarity at a degree of integration (I) of 1. Consequently, the findings presented in Table 2 demonstrate the absence of a unit root issue while employing the first difference. Therefore, we are now allowed to proceed with the implementation of the dynamic ARDL regression model, as recommended by Jordan and Philips (2018).

In order to go to the ultimate phase of implementing the DARDL strategy, it is important to ascertain whether there exists a long-term association between the dependent and explanatory variables. We used "Pesaran et al.'s (2001) ARDL bounds testing" technique to determine the presence of a long-run cointegration. Table 3 shows the results of the cointegration process. It reveals that CO_2, GDP, GDP^2, POP, and NEG have a long-run cointegration, which is supported by the F-statistics value, and the F-statistics is statistically significant at the 1% level.

Table 4 presents an analysis of the correlation between the variables under investigation. The long-term coefficients from the DARDL technique show that a rise in per capita GDP leads to increases in CO_2e in both long and short runs. This research backs up the EKC phenomena in the USA. This is supported by the fact that GDP is positive, yet its quadratic counterpart is significant and negative, demonstrating the necessary condition of the EKC hypothesis (Hasanov et al., 2021). By estimating the turning point, we can verify the sufficient condition for proving EKC. "The turning point must be within the sample range and the estimated elasticity for GDP must be positive and significant for the initial upward slope before becoming negative and significant on the downward sloping part, which means negative elasticity of the squared term of GDP. This is the sufficient condition for an estimated quadratic EKC (Hasanov et al., 2021)." The predicted inflection point of the EKC is calculated to be US$29581.156, as established using coefficient calculations, which is less than the highest per capita income in the USA of US $60836.77, confirming the EKC. The turning point occurred in the year 1977, which is within the chosen time range that also validates the existence of the EKC. The current study's primary discoveries are substantiated by existing scholarly literature (Hasanov et al., 2021; Pata, 2021; Alola and Ozturk, 2021). The findings, however, contradict those of Azam and Khan (2016) for high-income nations and Dogan and

Table 2
Unit root test.

Variable	Form	ADF (t-statistics)	PP (t-statistics)	Order of Integration
$lnCO_2$	Level	−2.683 (0.212)	−1.875 (0.626)	I(1)
	First Difference	−4.062** (0.053)	−6.139*** (0.000)	
lnGDP	Level	−1.288 (0.878)	−1.219 (0.895)	I(1)
	First Difference	−5.408*** (0.000)	−7.498*** (0.000)	
$lnGDP^2$	Level	−1.354 (0.843)	−1.875 (0.718)	I(1)
	First Difference	−5.892*** (0.002)	−4.982*** (0.003)	
lnNEG	Level	−1.068 (0.811)	−1.438 (0.791)	I(1)
	First Difference	−7.298*** (0.000)	−7.008*** (0.000)	
lnPOP	Level	−1.127 (0.880)	−0.893 (0.954)	I(1)
	First Difference	−6.210*** (0.000)	−7.892*** (0.000)	

"Note: Probability value is given in parenthesis. *** denotes a 1% level of significance, ** denotes a 5% level of significance, and * denotes a 10% level of significance."

Table 3
Co-integration test.

Empirical model	$lnCO_2 = f$ (lnGDP, $lnGDP^2$, lnNEG, lnPOP)	
Optimum lag length	1, 2, 1, 1, 3	
F- statistics	6.461***	
Significance level	**Lower bound I(0)**	**Upper bound I(1)**
1%	4.39	5.77
2.5%	3.92	5.12
5%	3.66	4.82
10%	3.01	4.14

"Note: *** denotes a 1% level of significance."

Table 4
Long and short-run coefficient estimates from the DARDL model.

Variables	Coeff.	Std. Error	t-stat
lnGDP	0.849***	0.115	8.56
ΔlnGDP	0.366***	0.080	5.08
$lnGDP^2$	−0.069**	0.027	−2.54
$ΔlnGDP^2$	−0.052**	0.024	−2.18
lnNEG	−0.819***	0.161	−5.08
ΔlnNEG	−0.181	0.138	−1.31
lnPOP	0.903***	0.178	5.08
ΔlnPOP	0.013*	0.007	1.86
Cons.	0.829**	0.372	2.23
ECT (-1)	−0.689***	0.159	−4.33
R^2	0.971	Adjusted R^2	0.982
F- Statistics [Prob.]	109.99[0.000]	Simulation	5000
Turning point	GDP per capita = US$ 29,581.156 Year = 1977		

"Note: *** denotes a 1% level of significance, ** denotes a 5% level of significance, and * denotes a 10% level of significance. The turnaround point has been calculated as per Shahbaz and Sinha (2019)."

Ozturk (2017) for the USA. The "inverted U-shaped EKC" shows that the USA's economic growth route is friendly to the environment and aligns with the USA government's objective of charting cleaner growth.

As expected, nuclear energy generation descends CO_2 emissions in the USA. With all other explanatory factors held constant, a 1% escalation in the NEG dwindles the CO_2 emissions by 0.82% in the long run and 0.18% in the short run. This suggests that increasing nuclear power generation by 1.22% (1/0.82) will cut CO_2 emissions by 1% over the long term and by 5.56% (1/0.18) will do so over the short term. As a result, the long-term environmental benefits of nuclear energy generation outweigh the short-term ones. Nuclear power generation is a carbon-free technology that is environmentally friendly. Besides, other gases (mostly inert gases) discharged into the atmosphere during this process are not as vast or diversified as emissions from fossil fuel burning (Hassan et al., 2022). Even though nuclear power produces essentially no GHG at the power plant level, it ranks the lowest among electricity-generating options in terms of lifetime GHG emissions (Weisser, 2007). Nuclear energy generates power via the uranium-fed fission method, making it more environmentally benign than any other fossil fuel. As a result, we might argue that nuclear energy's adoption and broad use improves environmental protection and reduces reliance on fossil fuel production and consumption-related environmental dangers. The results of our study align with the conclusions reported by Baek and Kim (2013), Lau et al. (2019), and Kim (2021). Nevertheless, there appears to be a contradiction between the findings of Jin and Kim (2018) and Nathaniel et al. (2021). The observed outcome may be ascribed to the swift substitution of fossil fuels with nuclear energy sources upon their availability, resulting in a decline in fossil fuel production and usage, and a restoration of biocapacity. Surprisingly, we found that the NEG's short-run influence is insignificant because the benefits of nuclear power deployment may not be apparent in the short term.

The empirical findings suggest that there exists a positive and statistically significant relationship between the long-term coefficient of total population size and CO_2e. Specifically, the results indicate that a 1% increase in population size is associated with a 0.90% increase in CO_2e. Similarly, the short-term population size coefficient is also positive and significant, but its influence on environmental deterioration is less than the long-term consequences. Our findings resonate with the results of Hussain and Rehman (2021), Usman and Hammar (2021), and Li and Haneklaus (2021). While the growing population is vital for economic development, it needs a well-thought-out strategy to ensure long-term environmental viability. The rising population consumes oxygen, food, and other essentials at an alarming level (Mohsin et al., 2019). This enormous demand for food has resulted in significant deforestation and environmental deterioration. In the USA, the ecological system's ability to absorb garbage created by economic activity is out of balance with population expansion. Thus, unchecked population expansion leads to urban congestion, increased energy use, and increased demand for natural resources, which wreak havoc on the environment. As the world's second-leading CO_2 emitter, an unforeseen increase in population size while remaining apathetic about environmental harm would pose a severe danger to the USA's goal of carbon neutrality by 2050.

The estimated "error correction term (ECT)" coefficient has a statistically significant negative value, indicating that divergence from the long-term equilibrium link will be rectified. With the contribution of the study's explanatory factors, we found a convergence speed of over 69% on an annual basis as the outcome of ECT.

One notable characteristic of the DARDL model is its capability to facilitate the graphical representation, modeling, and prediction of counterfactual alterations in a dependent variable due to a shock in an explanatory variable. The figures below show the counterfactual simulations recorded by the DARDL model. Fig. 3 illustrates the significant impact of a 10% increase or reduction in economic growth on CO_2e levels in the USA both in the short-term and long-term. However, in the long run, a 10% rise in GDP in the USA reduces the environmental state, and a 10% drop in economic development drastically decreases CO_2e. The curvature of the curve is steep in both scenarios with a 10% rise or dwindle in GDP, indicating that environmental quality is highly subject to economic endeavours.

Based on the information shown in Fig. 4, it can be inferred that alterations in nuclear energy generation, namely a 10% increase or decrease, have significant implications for both immediate and prolonged periods in relation to CO_2e in the USA. In light of the significant CO_2e consequences associated with both scenarios, our analysis utilizing a DARDL model reveals that the attainment of environmental sustainability may be facilitated with a 10% augmentation in nuclear energy generation. In addition, Fig. 5 demonstrates that a 10% positive or negative shock in population size causes substantial short- and long-term fluctuations in CO_2 emissions in the USA. The USA may achieve a sustainable environment by paying greater attention to population growth rates, and individuals should be more mindful of their emission activities which might have negative consequences for the environment. This ensures environmental security and is in a static state in the long run.

The scope of our inquiry was broadened with the implementation of further tests for diagnosis on the time-series data. The results are presented in Table 5. To detect the presence of serial autocorrelation, we employed the "Breusch-Godfrey LM test". The findings indicate that our model exhibits no evidence of serial autocorrelation. We also used the "Breusch-Pagan-Godfrey test", which illustrates that no issue of

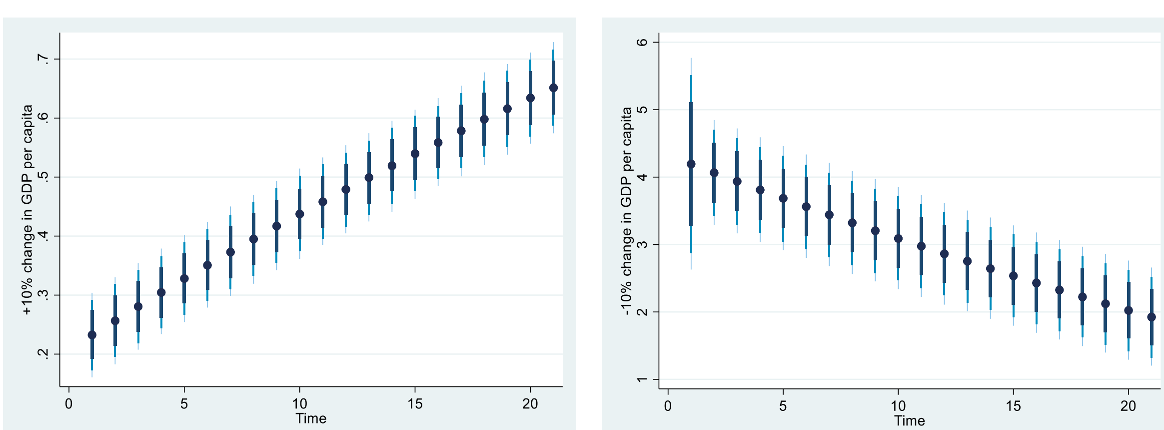

Figure 3. Economic growth and environmental quality deterioration. The above figure signifies a 10% increase or decrease in GDP per capita and its effect on CO_2 emission in the USA. The dots present the predicted value, whereas the deep blue to light blue lines show the 75%, 90%, and 95% confidence intervals, respectively."

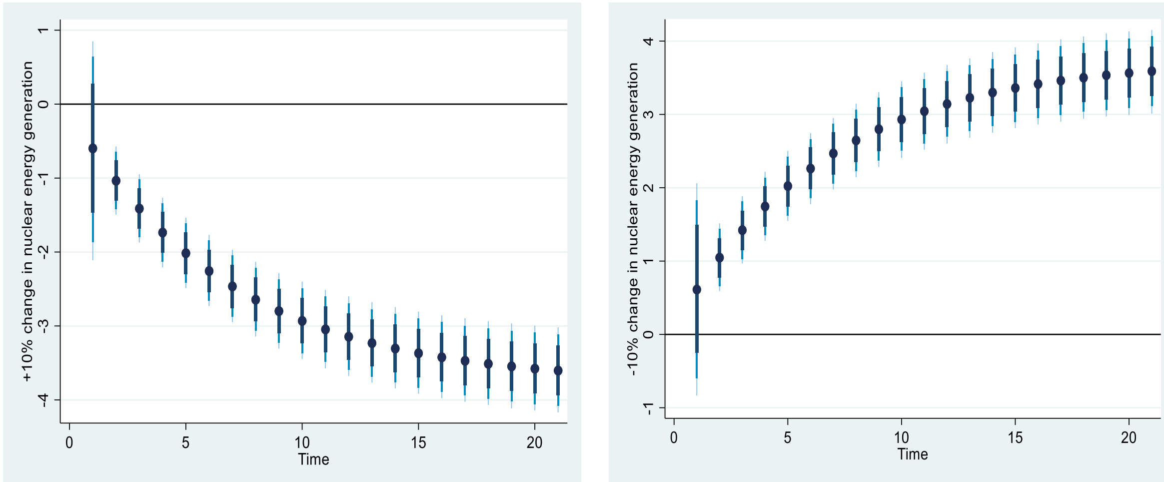

Figure 4. Nuclear energy generation and environmental quality deterioration. The above figure signifies a 10% increase or decrease in nuclear energy generation and its effect on CO_2 emission in the USA. The dots present the predicted value, whereas the deep blue to light blue lines show the 75%, 90%, and 95% confidence intervals, respectively."

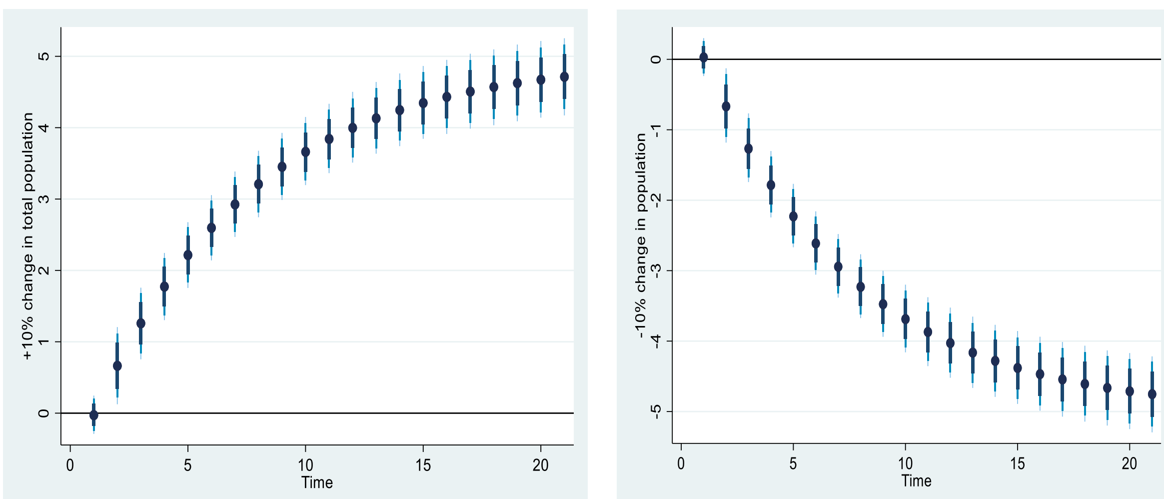

Figure 5. Population size and environmental quality deterioration. The above figure signifies a 10% increase or decrease in total population and its effect on CO_2 emission in the USA. The dots present the predicted value, whereas the deep blue to light blue lines show the 75%, 90%, and 95% confidence intervals, respectively."

Table 5
Outcomes of diagnostic tests.

Test name	Statistics	Inference
Breusch-Godfrey serial correlation LM test	F-stat.: 0.859 Prob.: 0.528	No issue of serial correlation
Jarque-Bera test	χ^2: 1.032 Prob.: 0.655	The distribution of error terms is normal
Breusch-Pagan- Godfrey test	F-stat.: 1.183 Prob.: 0.432	Homoscedastic
Ramsey RESET test	F-stat.: 1.983 Prob.: 0.321	Correct model specification

heteroscedasticity. Based on our research, the empirical model exhibits complete normality and is adequately characterized. In conclusion, the "CUSUM and CUSUMQ" tests were employed to verify the stability of our model. The plots created exhibit a placement within the 95% critical bound, confirming the stability of our framework, as visually depicted in Fig. 6. To assess the robustness of the DARDL model, the standard ARDL model was also employed. Table 6 displays the results obtained using the traditional ARDL model, demonstrating that all variables' long-run coefficients exhibit consistent signs with those observed in the DARDL, suggesting the reliability of our model. Therefore, the model is very appropriate as a foundation for making policy recommendations.

5. Conclusion and policy implications

The global environmental menace across the globe has raised concerns among policymakers and energy/environmental specialists. The environmental problems stem mainly from anthropogenic activities from human activities such as exploration and exploitation of natural resources to foster economic progress; this occurrence is predominant in highly industrialized economies such as the USA. Furthermore, the depletion of fossil fuel reserves and the environmental concerns

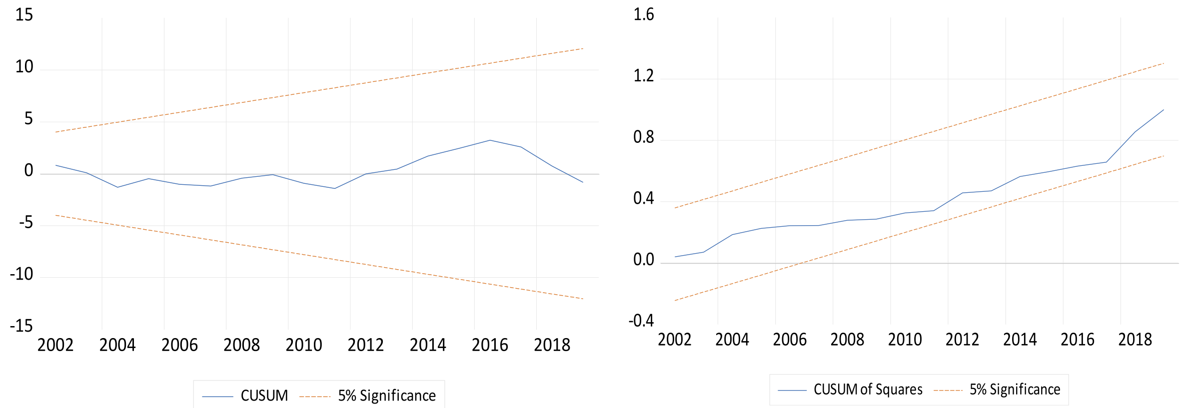

Fig. 6. The depiction of "CUSUM and CUSUM of square" test.

Table 6
Findings of the conventional ARDL model.

Variable	Coeff.	Stand. Error	t-value
lnGDP	0.241*	0.122	1.98
$lnGDP^2$	−1.22***	0.250	4.88
lnNEG	−0.661**	0.285	2.31
lnPOP	0.262	0.164	1.60

associated with their usage have prompted global stakeholders to consider other energy options that are both ecologically sustainable and have low carbon emissions. Nuclear energy is among the viable alternatives being considered. To this end, the present research article explores the nexus between "economic growth (GDP), population, and nuclear energy generation and environment" using the "dynamic autoregressive distributed lag model" in the context of the USA, which is the largest nuclear energy producers and a major carbon emitter.

The present study has successfully demonstrated a statistically significant long-term equilibrium connection between the variables of interest. This means that the variables are empirically linked and consistent with the prior theoretical expectations. The validation of the EKC concept for the USA is that the USA economy is still at its scale stage where the focus is on economic expansion, and there is a compromise for the quality of the environment. The plausible explanation is tied to the fact that the USA is a highly industrialized economy with the presence of many "multinational corporations (MNCs)" whose operations emit tons of carbon dioxide and nitrogen dioxide since their primary sources of energy come from dirty fossil fuels. The policy implications of this finding are that there is a need for more green growth policies to speed up the gradual phasing out of dirty fossil fuels from the energy mix and switch to the development and use of nuclear and renewable energies on a sustainable energy goal. Another measure to help circumvent dirty growth is to introduce "polluter pays principles (PPP)", a concept that emphasizes the need to obligate environmental regulation(s) on companies, especially MNCs that pollute the environment to the cost of damaging the environment.

Furthermore, there is also the need for population control in the USA, as our study indicated that an increase in population decreases the state of the environment (i.e., rapid population growth increases CO_2e). The policy response to this should be enforcement of population and sensitization to regulate population-induced CO_2e levels in the USA. From the empirical outcome of the importance of energy security in the USA which has become a concern in recent years, the global energy demand is plagued with a trade-off for environmental quality. This concern has heightened the energy-growth and sustainability debate. The present study adds to the extant literature by highlighting the pertinent mitigating role of nuclear energy generation as an alternative to fossil-fuel-based energy like coal that reduces environmental quality.

The present study's empirical results outline that the USA can reduce its CO_2e level by increasing nuclear energy consumption. i.e., more nuclear energy and electricity generating plants. The push for safe development and uses of nuclear energy is desirable and encouraging given the increase in USA investment in nuclear energy sources. Thus, government administrators in the USA are enjoined to pursue policies that promote the building of more nuclear plants that will foster a cleaner environment, increased energy supply, and energy security. This preposition coincidentally aligns with the USA energy target for 2030 on decarbonization goals and requires a collective effort and commitment from all stakeholders. Thus, there is also a need for investment in "research and development (R&D)" in the reorientation of the populace to benefit and potential of nuclear energy generation in mitigating climate change and the adoption of new modern technologies that circumvent the fear of radiation as it is commonly perceived in many quarters.

The main limitation of the current article does not account for other demographic indicators like democracy, and urbanization, as its main focus is on the impact of nuclear energy on CO_2 emissions for a developed economy like the USA. Future research works can explore other CO_2 emission determinants and other renewable options other than nuclear energy like solar, photovoltaic, hydro energy, urbanization, etc. The present article was concentrated on the USA. Future studies can also examine the theme using disaggregated data from other developed economies like G-7 economies or highly industrialized and developed economies like China and other regions of America like South and North American economies. Additionally, this study completely focused on the "inverted U-shape" of the EKC; however, future research can take the "N-shape" of the EKC into account in the case of the USA to reflect the actual income-emission nexus scenario and comprehend the income point from which emission is amplified due to rising income.

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

Data will be made available on request.

"Abbreviations list

USA	United States of America
DARDL	Dynamic Autoregressive Distributed Lag
SDGs	Sustainable Development Goals
EKC	Environmental Kuznets Curve

IPAT	Impact, Population, Affluence, and Technology
ZEC	Zero-emission Credit
TWh	Terawatt-hour
EIA	Energy Information Administration
ARDL	Autoregressive Distributed Lag
GHG	Greenhouse Gas
CVAR	Cointegrated Vector Autoregression
GMM	Generalized Method of Moments
FMOLS	Fully Modified Ordinary Least Squares
OECD	Organization for Economic Co-operation and Development
QQ	Quantile-on-quantile
UK	United Kingdom
VECM	Vector Error Correction Model
STIRPAT	Stochastic Impacts by Regression on Population, Affluence and Technology
GDP	Gross Domestic Product
WDI	World Development Indicators
ADF	Augmented Dickey-Fuller
PP	Phillips-Perron
CUSUM	Cumulative Sum
CUSUMSQ	Cumulative Sum Square
CO_2	Carbon Dioxide
ECT	Error Correction Term
MNCs	Multinational Corporations
PPP	Polluter Pays Principles
CO_2e	Carbon Dioxide Emissions
R & D	Research and Development"

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