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Original Article

Evaluating the asymmetric effects of nuclear energy on carbon emissions in Pakistan

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ABSTRACT

Achieving sustainable development requires an increasing share of green technologies. World energy demand is expected to rise significantly especially in developing economies. The increasing energy demands will be entertained with conventional energy sources at the cost of higher emissions unless eco-friendly technologies are used. This study examines the asymmetric effects of nuclear energy on carbon emissions for Pakistan from 1974 to 2019. Augmented Dickey-Fuller (ADF) and Phillips Perron (PP) unit root tests suggest that variables are integrated of order one and bound test of Autoregressive Distributed Lag (ARDL) and nonlinear ARDL confirm a long-run relationship among selected variables. The ARDL, Fully Modified Ordinary Least Squares (FMOLS), and Dynamic Ordinary Least Squares (DOLS) results show that the coefficient of nuclear energy has a negative and significant impact on emissions in both short and long run. Further, the NARDL finding shows that there exists an asymmetric long-run association between nuclear energy and CO_2 emissions. The vector error correction method (VECM) results indicate that there exists a bidirectional causal relationship between nuclear energy and carbon emissions in both the short and long run. Additionally, the impact of nuclear energy on ecological footprint has been examined and our findings remain robust.

1. Introduction

Climatic uncertainty and global warming are caused by the increasing concentration of carbon dioxide in the atmosphere [22]. The unsustainable consumption of energy threatens the environment, economy, and society [24] as 70% of emissions are associated with energy consumption and production [43]. Energy production based on fossil fuels is rich in carbon and comprises a major source of environmental degradation [13]. To meet Kyoto Protocol and COP-22 agreement the carbon emissions need to be controlled otherwise energy-related emissions will be doubled by 2050.

Ensuring energy security is pivotal for sustainable development. Energy security includes reliability of energy inputs to physical interruptions either natural or technological, and absence of price volatility. Energy-related emissions can be reduced through energy efficiency, the substitution of conventional carbon-rich technologies with low emission technologies including renewable and nuclear energy, and electrification of heat and transportation. Multiple options are required for decarbonization of the economies as no single option can alone achieve the target of 1.5 °C. Thus, to ensure energy security and decrease foreign fuel dependency, cheap and reliable energy sources are required as energy supports the growth and development of the economy.

Nuclear energy avoided 60 gigatons of carbon emissions over the past 50 years [25]. Nuclear plants do not produce greenhouse gases or pollution while operating and have very low emissions during their operational life delivering large quantities of energy [21]. Nuclear plants are cost-competitive and provide stable energy supplies and support growth and development and being immune to weather fluctuations make the economy climate-resilient. Nuclear plants have high initial capital costs while operating costs are minimized. Therefore, the prices of nuclear energy are predictable

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and remain stable for decades as fluctuations in nuclear energy are less obvious due to the cost structure of nuclear plants.

Nuclear energy being a low emission technology ensures a clean environment, thereby enhancing human health. Nuclear energy is evolving and providing more flexibility and efficiency. It provides access to reliable, cheap, and carbon-neutral electricity to developing economies which boost their development. It is dispatchable in nature. The mineral requirement of nuclear energy is lower than other energy sectors [43]. Electricity generated from nuclear plants increased from 2563 TWh [tetra watt hours] in 2018 to 2657 TWh in 2019 [45]. Furthermore, it is expected that the share of nuclear energy in world electricity generation will incline by 25% till 2050. According to Knapp & Pevec [27], nuclear energy can replace fossil fuel energy in a safe, reliable, economic, and sustainable way, therefore, the role of nuclear energy will be dominant in the energy transition.

The benefits of nuclear energy resulted in increased interest in exploring the influence of nuclear energy on environmental quality. After the declaration of the Paris Agreement, nuclear energy consumption has gained considerable attention. Many scholars [29,32] suggested that nuclear energy can resolve the energy security problems and environmental degradation, however, the nuclear power plant needs huge infrastructural development [33] and high capital costs which are scarce in developing countries [17]. Though the direct emissions from nuclear power plants are negligible, however, the footprints of small infrastructure facilities are greater than their benefits for the environment. Moreover, Al-Mulali [1] and Iwata et al. [23] also argued that nuclear energy accelerates carbon emissions. Nuclear energy is also faced with the challenges of radiation exposure, radioactive waste, off-site effects of nuclear accidents [21], and proliferation [9]. Furthermore, Gralla et al. [18] documented that the use of conventional energy and foreign dependency cannot be decreased through nuclear energy.

On the empirical side, the studies of Baek and Pride [5], Akhmat et al. [3], Lee et al. [29], Lau et al. [28], Xu [47] suggest a positive influence of nuclear energy in decarbonization while Saidi and Mbarek [41] and Jin and Kim [26] reported the insignificant effect of nuclear energy in decarbonization. However, the study of Mahmood et al. [33] suggests higher emissions resulting from nuclear energy. Thus, the empirical literature supports the deployment of nuclear energy to clean the environment, except for a few studies. The available studies mainly focus on a panel of economies [3,5,28,29]. Besides, these studies mainly focus on developed economies. Xu [47] focused on China while Mahmood et al. [33] focused on Pakistan, however, these country-specific studies provided contradictory findings. These studies assume a linear association between nuclear energy and environmental quality, ignoring nonlinear hidden effects. In addition, these studies employ CO2 emissions as a measure environmental quality which is considered a narrow measure in comparison to ecological footprint.

This study analyzed the influence of nuclear energy on emissions within the environmental Kuznets curve (EKC) framework. Several studies explored environmental quality and economic prosperity linkages within the EKC framework. The studies of Grossman & Krueger [19], Dinda [16], Copeland & Taylor [10], Tamazian & Rao [42], and Majeed & Luni [30] supported the validity of EKC while the studies of Azomahou et al. [4], and Begum et al. [6] reported N-shaped linkage between income and environmental quality. Furthermore, it is argued in the literature that the impact of climate change will be highest in developing countries [22,24].

Pakistan being a developing country needs drastic measures for energy transformation. Pakistan aims to expand nuclear power to support increasing energy demand. The two nuclear power plant sites in Pakistan are located at Chashma (300Mwe) and Karachi (90Mwe). Pakistan has 5 operatable reactors producing 1318MWe and two reactors are under construction which will add 2028 MWe. The nuclear share of generation stands at 6.6% [45].

It is very important to explore the behaviour of nuclear energy in reducing emissions in Pakistan. Pakistan as a developing country has been adversely affected by climate change. According to Wang et al. [44], Pakistan is the 6th populated country in the world, and despite being the 7th nuclear nation, it faces an energy crisis. It depends on imported fossil fuel for energy accessibility. For the last numerous decades, a persistent gap between energy demand and supply exists which leads to large economic and social losses. Furthermore, it is projected that the current electricity demand will be doubled in 2025. Consequently, Pakistan faces challenges related to environmental degradation and energy deficiency that need policy-level solutions immediately.

Against this background, we contribute to the literature in the following manners. First, we investigate the relationship between nuclear energy utilization and carbon emissions within the EKC framework for Pakistan over the period 1974 to 2019. To the best of the authors' knowledge, no prior study has explored the nuclear energy utilization and carbon emission nexus by considering the asymmetric relationships. Second, unlike prior studies which mainly focused on CO_2 emissions, we consider the influence of nuclear energy consumption on ecological footprint which represents environmental quality comprehensively. Third, the empirical literature on EKC validity lacks consensus and our study provides additional evidence in the presence of nuclear energy consumption. Fourth, this study employs nonlinear ARDL to explore both the short and long-run effects of nuclear energy on the environment.

The findings obtained will help energy experts, environmentalists, and development practitioners in formulating and implementation of policies that are environmentally friendly and can ensure environmental sustainability. This study will be helpful for economies, prioritizing investment in nuclear energy.

The study is structured as follows: Section 2 examines the relevant literature, section 3 is based on data description, model, and methodology, sections 4, 5, and 6 presents empirical findings from ARDL, NARDL, and robustness analysis, and section 7 provides the conclusion.

2. Literature review

The sustainable development goals are interlinked and indivisible. For achieving sustainability synergies in the decision-making are required at a global level. As the theory of sustainable development emphasizes the need to use resources in such a way that ensures the ability of resources for future generations to fulfill their demands. As the energy sector is heavily dependent on the extraction of fossil fuels which are limited in quantities and decreasing due to high extraction to meet the increasing demands thereby compromising the ability of future generations to use this resource. Therefore, resources that ensure sustainability are required in this regard nuclear energy is the potential option which is dependent on uranium.

The literature is divided into two subsections: Section 2.1 provides literature related to nuclear energy and environmental degradation while section 2.2 is based on economic growth and environmental degradation nexus.

2.1. Nuclear energy-environment nexus

Nuclear energy substitutes fossil fuels which generate 2 gigatons of carbon dioxide every year that can help in decarbonization at a low cost and within a short period of time, Nuclear plants use uranium [as fuel which is an inexhaustible energy source] that is widely distributed in five continents while fossil fuels are found in few politically sensitive areas thereby making it less vulnerable to disruptions and fuel supply [8]. Nuclear plants can be constructed in a way that makes them less prone to climate change and can help in synthetic fuels for the transportation sector further contributing to a reduction in emissions. The two distinctive features of nuclear energy from hydrocarbons are that nuclear plants generate heat without contributing to emissions and hazardous material is kept inside the fuel in the nuclear fusion process, thereby reducing its overall footprint. Furthermore, emissions resulting from nuclear plants result from the use of fossil fuel throughout its life cycle which can be reduced with the substitution of non-emitting fuels. It is also recognized that emissions from nuclear plants during their whole life cycle are similar to renewable energy sources thereby suggesting it's a source that helps in decarbonization and reduces human health impact from other energy sectors [34,43].

Along with emission reduction, it can contribute to medical and industrial applications as well. The number of people benefiting from nuclear medicine is increasing and about 30 million people benefit from it each year. Furthermore, 1.8 million pollution-related deaths are prevented due to nuclear power globally between 1971 and 2009. Nuclear energy ensures food security by exposing food to gamma rays that increase food shelf-life and kills bacteria. It also supports the management and conservation of water supplies and the identification of new sources along with water desalination. The energy density of nuclear fuel is greater than other fuels and environmental impact much lower, thereby nuclear plants use less land, and resource requirement are also limited when compared to other sources, thus having minimal impact on biodiversity worldwide [43].

Nuclear plants create highly radioactive material which is treated as waste and needs proper shielding and disposing of as it is dangerous. All energy sectors produce hazardous waste if not managed leads to contamination of the environment, therefore management is crucial. The waste generated from nuclear plants is in small volumes, managed and disposed of safely, not dispersed in the environment, and recyclable. Nuclear plants can affect the aquatic environment and lead to water stress as they need water for cooling purposes and 66% is released back into the environment as heat. However, ecosystem stress can be mitigated through careful plantation that reduces water and aquatic species stress. Nuclear plants with cogeneration lead to an increase in thermal efficiencies and reduce aquatic impact. Furthermore, the ratio of death associated with nuclear energy is low as compared to other energy sources however displacement [resettlement] is high [43].

The empirical literature analyzing the association between nuclear energy, and carbon emissions can be classified based on their finding. Several studies have explored that nuclear energy utilization contributes to a decline in emissions. Such as Baek & Pride [5] by employing multivariate cointegrated vector autoregression [CVAR] reported a decline in carbon emissions due to nuclear energy for the top six nuclear-generating countries. Akhmat et al. [3] also suggested a decline in emissions for 35 developed economies between 1975 and 2012. Lee et al. [29] by employing "panel dynamic ordinary least square [DOLS]" supported a decrease in the level of CO_2 emissions from nuclear energy utilization for 18 economies. Lau et al. [28], has explored the same finding for 18 "Organization of Economic Cooperation and Development [OECD]" economies by employing the "generalized method of moments and fully modified ordinary least square [FMOLS]". Moreover, Xu [47] argued that as compared to coal power, nuclear energy consumption produces fewer carbon emissions. Hassan et al. [20], reported a decline in emission from nuclear energy however this decline is less than the renewable energy effect in Brazil, Russia, India, China, and South Africa [BRICS] using Continuously Updated Fully Modified [CUP-FM] and continuously updated bias corrected [CUP-BC]. Alola and Nwulu [2] also reported that the use of coal, gas, and oil energy damages environmental quality while nuclear energy contributes to environmental sustainability [EKC] in Russia using ARDL. Danish et al. [12], suggested a decline in emission from the production sector however it does not have an impact on consumption-based emissions for Organization for Economic Cooperation and Development economies [OECD] using Driscoll-Kraay [DK] standard errors. Another study by Danish et al. [11], also reported decline in emissions from nuclear energy over the long run for India using dynamic ARDL.

Another group of studies has opposite findings. Saidi & Mbarek [41] analyzed the nuclear energy emissions nexus and reported an insignificant influence of nuclear energy utilization on carbon emissions for 9 developed countries between 1990 and 2013. Similarly, Jin & Kim [26] investigated the nuclear energy utilization and emission nexus for 30 countries from 1990 to 2014 and reported an insignificant effect of nuclear energy on emissions. However, Sarkodie and Adams [38] for South Africa revealed higher level of emissions from nuclear energy in the short run for 1971–2017, using ARDL. Similarly, Mahmood et al. [33] reported an incline in emission in Pakistan because of nuclear energy for 1973–2017, by employing ARDL. In the relevant literature, except Mahmood et al. [33], no other study has analyzed the nuclear energy-environment nexus for Pakistan.

2.2. Economic growth-environment nexus

The theoretical underpinning of economic growth and deteriorating environmental quality nexus is based on the EKC hypothesis. It suggests that economic development is achieved at the cost of deteriorating environmental quality initially however after reaching a threshold level of economic development, individuals start paying for a safe environment, and consequently environmental quality improves. According to Grossman & Krueger [19], the relationship between environmental quality and economic development follows three stages namely "scale, composition and technique effects". The scale effect refers to an increase in emissions resulting from higher economic activities. However, with development transmission of the economy from agriculture to industrial and from industrial to service-based economy (composition effect) improves environmental quality due to the use of clean technologies (technique effect). Roca et al. [37] provide primarily three explanations for the inverted U-shape association between economic development and environmental deterioration. First, a healthy environment is considered a luxury good demand of which increases as income increases. Second with the development new technologies come and as a result environmental degradation decreases and lastly with development production process changes and the importance of services sector increases which leads to environmentally friendly production processes.

Several studies empirically examine the EKC relationship for different countries and provide mixed results. Some studies [2,10,11,16,30,42] have explored the EKC hypothesis and accept its validity. Other studies [4,6] reject the EKC relationship and explore linear or N- shape relationships, thereby suggesting that environmental quality will deteriorate after a certain income level.

From the literature discussed, it can be concluded that prior studies [5,26] provide divergent findings depending on the circumstances of these countries. These countries have modern technology, skilled labor, huge financial resources, have stable economic conditions, and have a major share of nuclear energy in the energy mix. So, the empirical literature lacks evidence about developing countries like Pakistan. So, the finding of these studies does not provide suggestions for Pakistan. Therefore, it is important to analyze the influence of nuclear energy on carbon emissions in a

Table 1
Variable description and source.

Variables	Description	Data Source
CO_2 emissions	"Metric tons per capita"	World Bank (2020)
Economic growth (GDP)	"Constant 2010 US$"	World Bank (2020)
Nuclear Energy	"Metric tons per capita"	British Petroleum (2020)

resource-scarce developing country like Pakistan.

3. Data and methodology

3.1. Data

The study examined the asymmetric linkages between nuclear energy, economic prosperity, and CO_2 emissions for Pakistan spanning from 1974 to 2019. The data for nuclear energy has been extracted from British Petroleum [7]. The data of "economic growth and carbon emission" is taken from World Bank [46]. Log-transformed variables are used for the analysis. Table 1 presents variable descriptions.

3.2. Methodology

To examine the relationship between carbon emissions, economic growth, and nuclear energy the empirical model of the study is adopted from the study of Dong et al. [15] and Mahmood et al. [33]. The empirical model is presented as

$$l[CO_2]_t = \alpha_\circ + \alpha_1 lNE_t + \alpha_2 lGDP_t + \alpha_3 lGDP_t^2 + \mu_\circ \quad [1]$$

where CO_2 presents the "carbon dioxide emissions", NE is "nuclear energy", GDP is "gross domestic product" and GDP^2 is "square of gross domestic product", t and μ shows "the time period and error term".

3.2.1. Model specification: ARDL

Literature suggests various econometric tools for estimating the Long Run (LR) and Short Run (SR) dynamics. This study employed the "Autoregressive distributed lag (ARDL) bound test" approach for exploring the association among nuclear energy, GDP, GDP^2, and carbon emissions. The advantages of ARDL include Firstly, it estimates the LR & SR dynamic at one time, via simple linear transformation regardless of integration of order 0 or 1. Secondly, it is preferable for a small sample and handle the data producing method in a general to specific and offers sufficient lags. Thirdly, it reduces the problems related to "non-stationary" time-series data. Fourthly, the specification of ARDL is equivalent to the standard error correction model (ECM), so the estimates of ARDL are neutral and consistent enough to be used for policy purposes. The estimated ARDL model can be presented as follow:

$$\Delta LCO2_t = \alpha_o + \alpha_1 LCO2_{t-1} + \alpha_2 LNE_{t-1} + \alpha_3 LGDP_{t-1} + \alpha_4 LGDP^2_{t-1} + \sum_{i=1}^{p} \alpha_1 \Delta CO2_{t-i} + \sum_{i=0}^{q} \alpha_2 \Delta NE_{t-i} + \sum_{i=2}^{r} \alpha_3 \Delta LGDP_{t-i} + \sum_{i=0}^{s} \alpha_4 \Delta LGDP^2_{t-i} + \mu_t \quad (2)$$

In equation (2) the coefficients enclosed with difference operators ($\alpha_1, \alpha_2, \alpha_3\ \alpha_4$) evaluate Short Run (SR) dynamics, while the terms with 1st lagged depict the Long Run (LR) association. The procedure of ARDL consists of the subsequent stages. The 1st stage is to select the proper standards for the lag length choice. In this study, we used Hannan-Quinn criteria. The 2nd stage is to check the null hypothesis for instance "H_o: $\alpha_1 \neq \alpha_2 \neq \alpha_3 \neq \alpha_4 \neq 0$" is to be analyzed counter to alternative hypothesis "H_1: $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = 0$". The conclusion related to the existence of cointegration is based on the F Statistic value. Pesaran et al. [36] introduce Lower Bound (LB) and Upper Bound (UB) critical values criteria are applied correspondingly. If the calculated F Statistic is greater than the critical value of UB at a 1% level of significance, it implies the rejection of the "null hypothesis" and confirms the co-integration among the variables.

The LR association among variables is more helpful for policy purposes if the trend of causality between the variables is identified. The cointegration between the variables demonstrates the presence of causality between the variables. In this study, we applied the vector error correction model (VECM) Granger Causality Test for examining the causal association among the variables. The method of VECM comprises of few stages. In the 1st stage, simple regression is conducted for getting the error correction model (ECM). If the error correction model (ECM) value is negatively significant then we move more through incorporating ECM in the model. For estimating the LR & SR causal relationship between variables t-statistic and Wald-statistic framework has been employed respectively. The experimental equation for vector error correction model (VECM) Granger Causality can be represented as;

$$\begin{bmatrix} \Delta \log(CO2)_{2t} \\ \Delta \log(GDP)_t \\ \Delta \log (GDP)^2_t \\ \Delta \log(NEC)_t \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \end{bmatrix} + \begin{bmatrix} \beta_{11,1} & \beta_{12,1} & \beta_{13,1} & \beta_{14,1} \\ \beta_{21,1} & \beta_{22,1} & \beta_{23,1} & \beta_{24,1} \\ \beta_{31,1} & \beta_{32,1} & \beta_{33,1} & \beta_{34,1} \\ \beta_{41,1} & \beta_{42,1} & \beta_{43,1} & \beta_{44,1} \end{bmatrix} \times \begin{bmatrix} \Delta \log(CO2)_{t-1} \\ \Delta \log(GDP)_{t-1} \\ \Delta \log (GDP)^2_{t-1} \\ \Delta \log(NEC)_{t-1} \end{bmatrix} + \sum_{i=1}^{p-1} \begin{bmatrix} \lambda_{11,i} & \lambda_{12,i} & \lambda_{13,i} & \lambda_{14,i} \\ \lambda_{21,i} & \lambda_{22,i} & \lambda_{23,i} & \lambda_{24,i} \\ \lambda_{31,i} & \lambda_{32,i} & \lambda_{33,i} & \lambda_{34,i} \\ \lambda_{41,i} & \lambda_{42,i} & \lambda_{43,i} & \lambda_{44,i} \end{bmatrix} \times \begin{bmatrix} \Delta \log(CO2)_{t-1} \\ \Delta \log(GDP)_{t-1} \\ \Delta \log (GDP)^2_{t-1} \\ \Delta \log(NEC)_{t-1} \end{bmatrix} + \begin{bmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \end{bmatrix} \times (ECT_{t-1}) + \begin{bmatrix} \mu_{1t} \\ \mu_{1t} \\ \mu_{1t} \\ \mu_{1t} \end{bmatrix} \quad [5]$$

3.2.2. Model specification: NARDL

To capture the nonlinear nature of the variables and analyze the LR relationship Shin et al. [39] by expanding the Pesaran et al. [36] ARDL- Bound Test method introduced the approach of Nonlinear ARDL. NARDL approach captures the nonlinear nature of variables.

$$CO2_t = \alpha_o + \alpha_1^+ NE_t^+ + \alpha_2^- NE_t^- + \alpha_3 GDP_t + \alpha_4 GDP_t^2 + \varepsilon_t \quad (6)$$

Equation (6) is the revised edition of equation (1) that divided the NE into dual distinct categories namely negative and positive. Here, our parameters are $\alpha = [\alpha_o, \alpha_1^+, \alpha_2^-, \alpha_3, \alpha_4,]$ and $NE_t = NE_O + NE_t^+ + NE_t^-$ are the vector of unknown LR parameters. Where NE_t^+ *and* NE_t^- denotes the "partial sum of negative and positive variation" in NE_t:

$$NE_t^+ = \sum_{j=1}^{t} \Delta NE_j^+ = \sum_{j=1}^{t} \max(\Delta NE_j, 0), NE_t^- = \sum_{j=1}^{t} \Delta NE_j^- = \sum_{j=1}^{t} \min(\Delta NE_j, 0) \quad (7)$$

Equation (7) is centered at "positive and negative partial sum decomposition" for investigating the asymmetric impact of NE on CO_2. By pursuing the approach of Shin et al. [39] following equation (NARDL) has been developed:

$$\Delta CO2_t = \omega_o + \delta_1 CO2_{t-1} + + \vartheta_2^+ NE_{t-1}^+ + \eth_3^- NE_{t-1}^- + \gamma_4 GDP_{t-1} + \tau_5 GDP_{t-1}^2 + \sum_{i=1}^{m} \complement_i \Delta CO2_{t-i} + \sum_{i=0}^{n} [\varnothing_i^+ \ \Delta NE_{t-i}^+ + \varnothing_i^- \ \Delta NE_{t-i}^-] + \sum_{i=2}^{o} \phi_i \Delta GDP_{t-i} + \sum_{i=0}^{p} \rho_i \Delta GDP_{t-i}^2 + \varepsilon_t \quad [8]$$

Where "m, n, o & p" are the lag order. Equation (6) is not competent to give an accurate explanation of the projected asymmetric coefficient because in this equation there is a possibility of the problem of concealed cointegration. So, to confront this issue restriction is levied on the coefficient of equation (6) for instance $\beta_1^+ = -\vartheta_2^+/\delta_1$ & $\beta_2^- = -\eth_3^-/\delta_1$. The Short Run [short-run] impact of the surge in NE on CO_2 emissions is estimated with $\sum_{i=0}^{n} \varnothing_i^+$ while the Short Run [SR] effect of the decrease in NE on CO_2 emissions is estimated with $\sum_{i=0}^{n} \varnothing_i^-$. Hence, this equation analyzed the asymmetric effect of LR & SR of NE on CO_2 emissions.

The error correction model [ECM] of equation (6) is described as:

$$\Delta CO2_t = \sum_{i=1}^{P} \Pi_i \Delta CO2_t + \sum_{i=0}^{a} [\psi_i^+ \Delta NE_{t-i}^+ + \psi_i^- \Delta NE_{t-i}^+] + \sum_{i=2}^{h} P_i \Delta GDP_{t-i} + \sum_{i=0}^{n} H_i \Delta GDP_{t-i}^2 + \Omega_i ECT_{t-1} + \zeta_t \quad (9)$$

Where " Π_i , P_i & H_i"are the Short Run coefficients and Ψ_i^+, Ψ_i^- denotes the SR symmetry modification. Furthermore, Ω_i states to the coefficient of error correction term (ECT).

The method of Nonlinear ARDL comprises subsequent stages: The 1st stage is to employ the unit root tests (URTs). The reason behind the URTs is to approve that all the variables are integrated of order zero and one or have combined order, but not of order two. So, for exploring the order of cointegration the conventional Augmented Dickey-Fuller (ADF) and Phillips -Perron (PP) URTs are employed.

In the subsequent stage by the technique of ordinary least square (OLS) equation, 8 is created. In another way, in this stage, we create the "positive and negative series" of NE because we intend to explore the asymmetric effect of NE on CO_2 emissions. After devising equation (8) for upgrading the finishing structure of the Nonlinear ARDL model "general to specific method" has been utilized by decreasing in-significant lags. In the later stage, a test for assessing the LR association among the variables is utilized by implementing the method of "bounds testing" techniques. The test comprises of Wald F Test. The null hypothesis is, H_o: $\delta_1 = \vartheta_2^+ = \eth_3^- = \gamma_4 = \tau_5 = 0$ whereas the alternative is H_1: $\delta_1 \neq \vartheta_2^+ \neq \eth_3^- \neq \gamma_4 \neq \tau_5 \neq 0$. Finally, along with the existence of co-integration, the LR & SR asymmetric effect of NE on CO_2 emissions is analyzed. Moreover, the Asymmetric Cumulative Multiplier Effect of 1% adjustment in NE_{t-i}^+ and NE_{t-i}^- is framed as:

$$K_b^+ = \sum_{j=0}^{b} \frac{\partial CO2_{t+j}}{\partial NE_{t-1}^+}, K_b^- = \sum_{j=0}^{b} \frac{\partial CO2_{t+j}}{\partial NE_{t-1}^-}, b = 1, 2, 3\ldots$$

It should be observed that as b $\rightarrow \infty$, $K_b^+ \rightarrow \beta_1^+$, & $K_b^- \rightarrow \beta_2^-$.

4. Analysis with carbon emissions

4.1. Unit root test results

In time series analysis, the first step is to check the stationarity of the variable. As it is necessary for unbiased and reliable results and preconditions for applying ARDL and NARDL. For employing ARDL and NARDL the series should be integrated of order zero or one but not at two. The stationary of the variables is checked through ADF & PP URTs. Table 2 illustrates the finding of the URTs both with level and 1st difference. The finding indicates that all the variables are non-stationary at level but become stationary at 1st difference. So, it is concluded that series are stationary, and we can go further for the cointegration analysis.

Table 2
Unit root test.

Variables	ADF test statistic		PP test statistic	
	Statistics	Probability	Statistics	Probability
	Level	1st Difference	Level	1st Difference
LCO_2	−2.364	−7.523	−2.262	−7.440
	(0.157)	(0.000)	(0.188)	(0.000)
LGDP	−1.493	−4.918	−1.148	−4.956
	(0.528)	(0.000)	(0.688)	(0.000)
$LGDP^2$	−1.241	−4.879	−0.888	−4.846
	(0.648)	(0.000)	(0.783)	(0.000)
LNE	−1.662	−7.523	−1.613	−8.187
	(0.443)	(0.000)	(0.467)	(0.000)

Probabilities are presented in parenthesis

Table 3
Unit root test.

Variables	ADF test statistic		PP test statistic		ADF Break Point	
	Level	1st Diff	Level	1st Diff	Statistics	Year
LCO_2	−2.364	−7.523	−2.262	−7.440	−3.1421	1991
	(0.157)	(0.000)	(0.188)	(0.000)	(0.1421)	
LGDP	−1.493	−4.918	−1.148	−4.956	−3.861	1989
	(0.528)	(0.000)	(0.688)	(0.000)	(0.074)	
$LGDP^2$	−1.241	−4.879	−0.888	−4.846	−4.282	1988
	(0.648)	(0.000)	(0.783)	(0.000)	(0.2086)	
LNE	−1.662	−7.523	−1.613	−8.187	−4.664	2000
	(0.443)	(0.000)	(0.467)	(0.000)	(0.000)	

Probabilities are presented in parenthesis.

Table 4
ARDL- bound test.

F Statistics 5.379				
10%	Lower Bound	2.01	Upper Bound	3.1
5%	Lower Bound	2.45	Upper Bound	3.63
2.5%	Lower Bound	2.87	Upper Bound	4.16
1%	Lower Bound	3.42	Upper Bound	4.84

Null Hypothesis: No cointegrating relationship exists.

4.2. Zvoit and Andrews unit root test

Additionally, the presence of structural breaks in the series is also detected by employing Zvoit & Andrews Structural URT. Perron [1989] highlighted that the existence of structural break, when overlooked in conventional URTs, yield biased experimental outcomes. So, structural breaks in unit root tests are significant to accommodate correct and impartial estimates. Unit root tests with structural break dates are illustrated in Table 3.

Table 5
Long run & short-run results of ARDL.

Long-run results of ARDL			
Variables	Coefficients	Std.Error	P-value
LGDP	−1.560***	0.088	0.000
$LGDP^2$	0.223***	0.012	0.000
LNE	−0.028*	0.015	0.069
Short-run results of ARDL			
D[LGDP]	−0.531***	0.172	0.003
D[$LGDP^2$]	0.075***	0.024	0.003
D[LNE]	−0.009*	0.005	0.067
Ect[-1]	−0.340***	0.097	0.001
Diagnostic tests			
LM Test	2.811	**Breusch Pagan Godfrey**	1.264
	(0.245)		(0.867)

***,* denotes 1% & 10% level of significance.

Table 6
Nonlinearity BDS test.

Variables	m = 2	m = 3	m = 4	m = 5	m = 6
LCO_2	0.1899***	0.3265***	0.4191***	0.4857***	0.5353***
LGDP	0.1833***	0.3014***	0.3771***	0.4389***	0.4885***
$LGDP^2$	0.1805***	0.2917***	0.3607***	0.3994***	0.4236***
LNE	0.0941***	0.1397***	0.1365***	0.1351***	0.1190***

Note: ***$p < 0.01$.

Table 7
FMOLS and DOLS.

	FMOLS			DOLS		
Variables	Coefficients	Std.Error	P-value	Coefficients	Std.Error	P-value
LGDP	−1.637***	0.066	0.000	−1.583***	0.120	0.000
$LGDP^2$	0.233***	0.009	0.000	0.224***	0.017	0.000
LNE	−0.030**	0.013	0.032	−0.039*	0.019	0.056

***,**,* represent 1%, 5% and 10% level of significance.

4.3. Results of cointegration test [ARDL]

After approving the stationarity of the variables, the succeeding stage is to check the cointegration between the concerned variables. In this analysis, we use Hannan-Quinn criteria for the choice of proper lag length. After it, we applied ARDL-Bound Test. Table 4 illustrates the result of the Bound Test. The results demonstrate that the LR relationship exists among the variables as the null hypothesis of no-cointegration is rejected.

The finding approves the existence of cointegration. So, we can move to the next step for LR & SR dynamics.

4.4. Estimates of long run (LR) and short run (SR) dynamics (ARDL)

For exploring the LR & SR dynamics in this study we employed ARDL. Table 5 reports the finding of LR & SR ARDL. The results demonstrate that all the variables are statistically significant in both LR & SR. According, to the finding the coefficient of Nuclear Energy (NE) in both LR & SR is negatively significant. Nuclear energy is one of the clear, reliable, and settled technology for electricity production. Because it produces zero emissions, and it does not diminish. Moreover, it decreases dependence on fossil fuels which pollute the environment. Furthermore, NE has the capacity to encounter the increasing demand for energy and decreases dependence on energy imports. These findings are parallel with the studies of Lee et al. [29] Lau et al. [28], Hassan et al. [20], Alola and Nwulu [2], and Danish et al., [11]. Our results depart from the findings of Sarkodie & Adams [38] and Mahmood et al. [33] as they reported higher level of emissions caused by nuclear energy. The reason behind positive impact of nuclear energy on environment is mismanagement in handling and disposal of nuclear waste and radioactive substances.

Furthermore, the coefficient of GDP is negative, and GDP^2 is positive indicating the "U-shaped" association between GDP per capita and carbon dioxide emissions. The results are consistent with Destek & Sinha [14], and Perman & Stern, [35]. According to these studies, economies like Pakistan are facing serious environmental issues with more economic growth. This is mostly because of the locational displacement of the dirty industry to these economies which means that very developed countries have extra obstructive ecological instructions and principles owing to which they shift pollution concentrated manufacture activities to low developed states expanding their pollution stock. This finding is inconsistent with Saint Akadırı et al. [48] who validated the EKC for Brazil, Russia, India, China and South Africa (BRICS) economies. The likely reason of this inconsistency could be different sampled countries and their development stage.

4.5. Nonlinearity BDS test

We have applied the Nonlinear BDS Test. Table 6 illustrates the finding found through the BDS Test in VAR containing "m" dimension. The finding indicates that nonlinearity exists as the null hypothesis of linearity gets rejected for all the variables. Therefore, the NARDL approach is appropriate for the further analysis.

Moreover, for the robust analysis, we also applied alternative cointegration methods such as FMOLS & DOLS. The finding of fully modified ordinary least square (FMOLS) and dynamic modified ordinary least square (DOLS) are presented in Table 7. These results confirm the "U-shaped EKC" between GDP per capita and CO_2 emissions. Moreover, findings indicate that NE has a negative effect on carbon dioxide emissions. So, the results of "FMOLS & DMOLS" are parallel with the finding of ARDL.

4.6. The VECM Granger causality test

The LR and SR dynamics provide information related to the nature of the association between the variables. But for efficient policy recommendation, it is important to scrutinize the direction of the causality among the variables. So, the VECM Granger Causality Test for exploring the direction of causality between the variables has been applied. Table 8 reports the findings of VECM. According to finding here exist a bidirectional causal association among NE and carbon emissions in the LR and SR.

5. Results of non-linear auto regressive distributed lag (NARDL)

5.1. Results of cointegration test (NARDL)

To examine the asymmetries in the LR and SR between carbon dioxide emissions and Nuclear Energy (NE), NARDL has been applied. The finding of the Nonlinear ARDL-bound test is presented in Table 9. The computed F Statistics (5.379) surpasses the UB critical value at a one percent level of significance demonstrating that nonlinear cointegration survives.

5.2. Estimates of long run (LR) and short run (SR) dynamics (NARDL)

Table 10 reports the findings of the LR and SR Nonlinear ARDL. The finding shows that there exists an asymmetric LR relationship between NE and CO_2 emissions. In LR positive NE have no effect on CO_2 emissions, while negative NE decreases the CO_2.

The coefficient of GDP is negative, and GDP^2 appears with a positive sign demonstrating the U-shaped association between GDP per capita and carbon dioxide emissions. These findings are aligned with Srinivasan [40] and Majeed & Mazhar [31]. According to these studies, South Asian countries are middle-income countries, and transformation from agriculture to manufacturing sector upsurge the problems related to the environment. The need for energy is also high owing to a large population and as a result, a "U-shaped" association exists among GDP per capita and CO_2 emissions in these economies.

In SR both positive and negative NE shock reduce the carbon emissions in Pakistan. The impact of negative NE shocks on a decline in carbon emissions is greater than positive NE shocks. The Error Correction Term (ECT) is negative and significant indicating that variation in the direction of equilibrium takes place and its speed is rapid. Furthermore, there is no issue of autocorrelation as suggested by the Lagrange multiplier test and heteroscedasticity as suggested by the Breusch Pagan Godfrey test.

5.3. Positive and negative components of nuclear energy

Through the asymmetric ARDL approach, we also fragmented the negative and positive components of NE. Fig. 1 shows the disintegrated negative component while Fig. 2 displays a positive component of nuclear energy obtained through Nonlinear ARDL.

5.4. CUSUM and CUSUM of the square

The stability of the LR and SR coefficient is checked through CUSUM and CUSUMSQ. The graphs demonstrated in Fig. 3 indicate that the variance and parameters remain insensitive using Cumulative Sum (CUSUM) and CUSUM of the Square at the significance level of 5%.

5.5. Dynamic multiplier graph (DMG)

For calculating nonlinearity, the Dynamic Multiplier Graph (DMG) is produced. Fig. 4 shows the DMG. This graph measures the variation of asymmetry in the long run for Negative and Positive shocks in NE. The asymmetric variation is obvious from Negative and Positive adjustment curves at a specific time.

6. Robustness analysis by measuring environment with ecological footprint

Tables 11–13 presents the estimated result done for the robustness of the finding. Findings reveal that nuclear energy declines ecological footprint in both LR and SR. Furthermore, results support a U-shaped association between income per capita and ecological footprint. This means our results are robust.

Table 8
Results of VECM Granger causality.

Dependent Variable	SR causality Wald statistic				LR causality t-statistic
	ΔLCO_2	ΔLGDP	$\Delta LGDP^2$	ΔLNE	ECT_{t-1}
ΔLCO_2	–	1.115**	−0.019*	−0.012	0.005
		(0.04)	(0.08)	(0.189)	(0.281)
ΔLGDP	0.104	–	0.877**	−0.006	−0.321*
	(0.187)		(0.016)	(0.323)	(0.085)
ΔLGDP2	1.298	−154.6**	–	−0.078	0.295*
	(0.179)	(0.017)		(0.351)	(0.097)
ΔLNE	0.135	23.191	−1.807	–	−0.221**
	(0.99)	(0.911)	(0.920)		(0.021)

***,**,* represents 1%, 5% and 10% level of significance; Probability in parenthesis.

Table 9
Nonlinear ARDL-bound test.

F Statistics 5.379				
10%	Lower Bound	1.9	Upper Bound	3.01
5%	Lower Bound	2.26	Upper Bound	3.48
2.5%	Lower Bound	2.62	Upper Bound	3.9
1%	Lower Bound	3.07	Upper Bound	4.44

Null Hypothesis: No cointegrating relationship exists.

Table 10
Long run and short-run results of NARDL.

Long-run results of NARDL			
Variables	**Coefficients**	**Std.Error**	**P-value**
LGDP	−1.416***	0.168	0.000
$LGDP^2$	0.202***	0.026	0.000
LNE^+	−0.026	0.016	0.109
LNE^-	−0.038**	0.015	0.019
Short-run results of NARDL			
D[LGDP]	−0.499***	0.157	0.002
D[$LGDP^2$]	0.071***	0.022	0.003
$D[LNE]^+$	−0.009*	0.005	0.090
$D[LNE]^-$	−0.013**	0.005	0.010
Ect[-1]	−0.352***	0.087	0.000
Diagnostic Tests			
LM Test	2.923 (0.231)	Breusch Pagan Godfrey	1.814 (0.874)

***, **, * represents 1%, 5%, and 10% level of significance.

7. Conclusion

Nuclear energy is capable of producing carbon-free electricity and supports environmental sustainability, economic growth, food security, and water desalination. As nuclear energy has the potential of supplying uninterrupted energy, therefore, the study analyzed the linkages between nuclear energy utilization consumption, economic growth, and carbon emissions for Pakistan over the period of 1974–2019. The techniques ARDL, FMOLS, DOLS, and Nonlinear ARDL are used for empirical analysis. Moreover, causality between the variables is examined by using the VECM Granger Causality Test.

The findings of ARDL show that the coefficient of nuclear energy is negative in both LR and SR. The finding of FMOLS and DOLS are consistent with ARDL. The empirical findings obtained from Nonlinear ARDL support the asymmetric associations between NE and CO_2. In LR positive NE does not influence carbon emissions whereas negative NE decreases the CO_2. In SR both positive and negative NE shock decrease the CO_2 emissions in Pakistan. The results of VECM support bidirectional causality among NE and CO_2 emissions in LR and SR.

Finding suggests that the introduction of nuclear technologies will decrease the use and dependence on coal and oil consumption and CO_2 emissions can be eliminated. Further, the development of the nuclear energy sector helps in the modernization of the energy sector. Nuclear power is cost-competitive, climate-resilient, high-energy-density, and a stable source of energy. Besides, it ensures price stability, improves energy security, decarbonizes the environment, and its generated heat and hazardous material are kept inside the fuel, thereby lowering its footprint. Contrary to this, nuclear power has certain concerns as well such as radiation exposure, radioactive waste, nuclear accidents, and proliferation. Moreover, nuclear power plants are expensive to build. To reduce the risk (radiation) associated with nuclear energy, the government can introduce stringent rules and control aimed at maintaining the radiation exposures within specified limits for workers and members of the public. The government may encourage clean energy (nuclear) usage for the fulfillment of energy requirements of the country. Moreover, economic prosperity can be achieved through

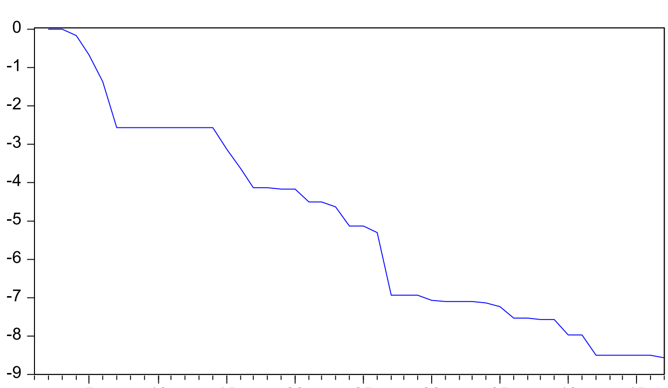

Fig. 1. Negative component of nuclear energy.

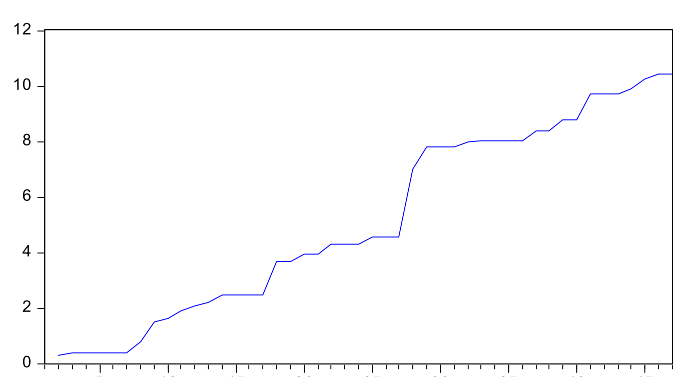

Fig. 2. Positive component of nuclear energy.

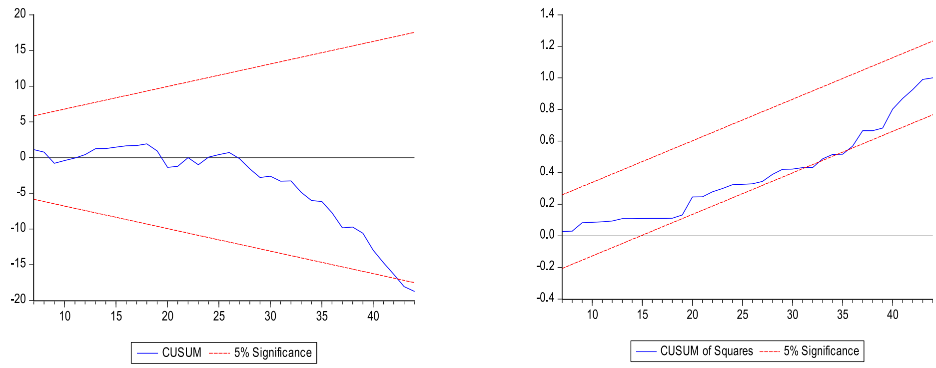

Fig. 3. Cumulative sum (CUSUM) & CUSUM of square.

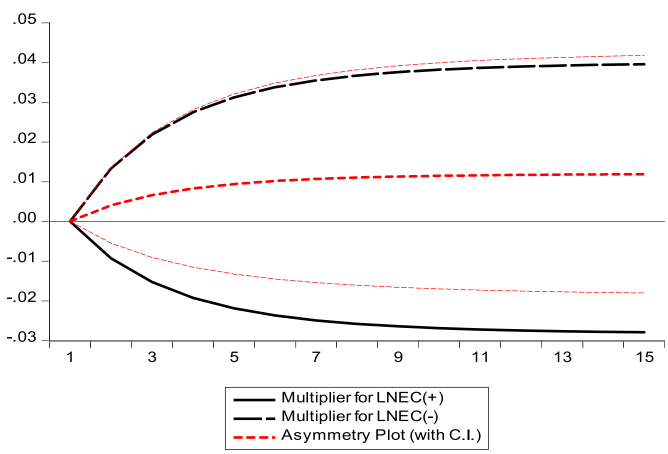

Fig. 4. Dynamic Multiplier Graph. Note: LNEC is Nuclear Energy. Years are plotted on the horizontal axis and the magnitude shocks [+ and -] on the vertical axis.

eco-friendly practices. Future studies can focus on the linkages between NE and renewable energy along with energy efficiency in the decarbonization of the economy.

Table 11
Long run and short-run results of ARDL.

Long-run results of ARDL			
Variables	**Coefficient s**	**Std.Error**	**P-value**
LGDP	0.042***	0.010	0.000
LGDP²	−0.187**	0.077	0.020
LNE	−0.032*	0.019	0.099
Short-run results of ARDL			
D[LGDP]	0.012***	0.004	0.006
D[LGDP²]	−0.055**	0.023	0.026
D[LNE]	−0.009*	0.005	0.067
Ect[-1]	−0.295***	0.090	0.002
Diagnostic Tests			
LM Test	2.229	**Breusch Pagan Godfrey**	7.017
	(0.327)		(0.135)

***, **, * represents 1%, 5% and 10% level of significance.

Table 12
FMOLS and DOLS.

	FMOLS			DOLS		
Variables	Coefficients	Std.Error	P-value	Coefficients	Std.Error	P-value
LGDP	0.083***	0.009	0.000	0.056***	2.66	0.000
LGDP²	−0.617***	0.067	0.000	−0.432***	5.68	0.000
LNE	−0.029**	0.013	0.037	−0.029***	4.00	0.000

***, **, * represents 1%, 5% and 10% level of significance.

Table 13
Long run & short run results of NARDL.

Long-run results of NARDL			
Variables	Coefficients	Std.Error	P-value
LGDP	−0.496**	0.230	0.037
LGDP²	0.067*	0.037	0.077
LNE⁺	−0.039	0.024	0.115
LNE⁻	−0.050*	0.025	0.055
Short-run results of NARDL			
D[LGDP]	−0.166**	0.071	0.026
D[LGDP²]	0.022*	0.011	0.050
D[LNE]⁺	−0.013**	0.006	0.049
D[LNE]⁻	−0.016*	0.009	0.085
Ect[-1]	−0.334***	0.122	0.009
Diagnostic Tests			
R-squared	0.891		
LM Test	2.364	**Breusch Pagan Godfrey**	7.790
	0.306		0.168

***, **, * represents 1%, 5% and 10% level of significance.

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.

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