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The role of nuclear energy in the correction of environmental pollution: Evidence from Pakistan

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ABSTRACT

The global warming phenomenon emerges from the issue of climate change, which attracts the attention of intellectuals towards clean energy sources from dirty energy sources. Among clean sources, nuclear energy is getting immense attention among policymakers. However, the role of nuclear energy in pollution emissions reduction has remained inconclusive and demand for further investigation. Therefore, the current study contributes to extend knowledge by investigating the nexus between nuclear energy, economic growth, and CO_2 emissions in a developing country context such as Pakistan for the period between 1973 and 2017. The auto-regressive distributive lag model summarizes the nuclear energy has negative effect on environmental pollution as it releases carbon emission in the environment. Moreover, vector error correction Granger causality provides evidence for bidirectional causality between nuclear energy and carbon emissions. These interesting findings provide new insight, and policy guidelines provided based on these results.

1. Introduction

Since the ratification of the Kyoto Protocol under the umbrella of the United Nations (UN) in 1997, countries around the world are struggling to reduce global warming. Leaders and policymakers showed seriousness and more dedication by endorsing the “Paris Agreement” in 2015 to tackle the underlying problem in a progressive way. The “Paris Agreement” considered an endorsement and recognition of the scientific work by scholars and the commitment of policymakers to combat the issue of global warming. The objective is to reduce the earth's atmospheric temperature by 2 °C at the pre-industrial level.

The adverse consequences of environmental pollution resulted in rising global temperature, disordering weather patterns, air pollution, oceans acidification, rising sea level, floods, hurricanes, droughts, extreme heat wavess, infertility, health problems and a lot of other dangers to humanity [1]. The fossil fuel burning is the main culprit behind global warming which resulted in greenhouse gases (GHG) emissions led by carbon dioxide (CO_2) emission, key contributor to environmental pollution [2]. The rising CO_2 emissions intensity and global warming complexities have raised the importance to focus on alternative energy generation options. The serious concerns over fossil fuel consumption, issue of energy security, and GHG emissions challenges have brought attention to clean energy sources among public and policy analysts as well. Clean energy options (nuclear energy and renewable energy) have emerged as alternate energy source and effective tools to combat the hazards of climate change [3,4]. As a part of the new energy policy strategy, many countries are focusing on increasing the share of nuclear energy supply to diversify energy supply, reduce dependence on imported fossil fuels with volatile prices, increase energy stability and security [5].

During the last four decades, nuclear energy consumption has increased by more than 40%, by generating 12% of the world's electricity and accounted for 5% of global primary energy demands in 2018 [6,7]. Nuclear energy has a considerable potential to meet the rising energy demands and combat environmental pollution

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problems promptly [8]. Thus, the remarkable growth of nuclear energy has resulted in rising interest among scholars. Especially, nuclear energy has gained a more advantageous position after the promulgation of the "Paris Agreement". As it binds signatories to substantially cut off their GHG emissions to reduce global warming [8]. Many scholars believe that nuclear energy as a solution to counter the problem of energy security and global warming [9–11]. At the same time, many believe it harms the environment and humanity [12,13].

Against this background and to best of authors' knowledge, no empirical study has attempted to investigate the role of nuclear energy in environmental pollution reduction within the framework of environmental Kuznets curve (EKC) in a developing country context like Pakistan. So a study from a developing country like Pakistan is essential to know the behavior of nuclear energy in environmental mitigation and economic perspective. The study findings will be fascinating to provide specific policy recommendations as well as research directions. In addition, the study outcomes could be used for practical policy guidelines for other developing countries.

Pakistan's selection for the study is justified in several ways. Among developing countries, Pakistan's represents as a classic example of investigation. Pakistan is highly vulnerable to the adverse impacts of climate change but has done little contribution to the problem of global warming. Pakistan is the sixth most populous country in the world, and the 7^{th} declared nuclear nation, facing severe energy crisis [14]. The country heavily relies on imported fossil fuels for energy availability. A constant gap between energy supply and demand is prevailing from last several decades, resulting in huge economic and social losses. For instant, due to the power shortage, Pakistan's economy has suffered by US$ 18 billion (6.5% of GDP) only in the fiscal year 2015 [15–17]. Moreover, it is expected that the present electricity demand will be doubled in 2025. Thus, Pakistan is in a very dire condition, where both environmental degradation problems and a shortage of energy are coexisting and need policy level remedies instantly. Considering both present and future scenario, it is imperative to investigate the role of nuclear energy in environmental mitigation and economic development within particular circumstances of a developing country which have strong ambitions of nuclear energy growth. Due to different economic development patterns, resource availability constraints, environmental policies, geopolitical situations, legal restrictions on nuclear energy usage across different countries, many scholars suggested that country-specific investigation is essential to evaluate nuclear energy's role in pollution mitigation in Pakistan.

The contribution of the present study to extant literature as follows: First the current study fills the academic gap in the existing energy-emission nexus literature for investigating the role of nuclear energy in environmental pollution for first time in Pakistan. This study will not only provide country-specific policy directions but could be used in energy resource planning guideline by other developing countries. Second, against the previous literature we did not include other source of energy into empirical model in order to capture the real effect of nuclear energy in CO_2 emissions. Third, the study adapted most robust estimation tools such Bayer and Haneck cointegration test and autoregressive distributive lag (ARDL) model for the longest available dataset spanning from 1973 to 2017. Moreover, the results of the study have a broader scope, as most of the developing countries have to face almost the same resources restrictions like Pakistan.

The study proceeds further as follows: the second section comprises relevant literature discussion, third on data and model construction, fourth analysis and results, fifth the discussion part, and last the policy recommendations.

2. Literature review

The energy-growth-emission nexus has been widely discussed including aggregate and disaggregate energy (renewable and nonrenewable energy sources), taking different proxies of economic growth and environmental pollution indicators in different regions and countries with mixed results [18–23]. Recently, the importance of clean energy in environmental pollution is getting immense attention among scholars. Some authors have argued that clean energy sources help to mitigate CO_2 emissions [24–28]. Contrary to this, some scholar has agreed with the statement that clean energy sources contribute to environmental pollution [29–31]. Apart from this, few argue with insignificant effect of renewables on CO_2 emissions [32,33].

Meanwhile clean energy sources, as such nuclear energy gets immense attention in the literature. Nuclear energy has a positive role in reducing environmental pollution. Such as Lee [34] analyzed the nuclear energy relationship with CO_2 emissions in a panel of 18 countries by using panel dynamic ordinary least square (DOLS) method and found that nuclear energy mitigate level of CO_2 emission. Lau [35] find a similar result for nuclear energy in 18 Organization of Economic Cooperation and Development (OECD) countries by using panel fully modified ordinary least squares (FMOLS) and panel dynamic generalized method of moments (GMM) Using multivariate cointegrated vector autoregression (CVAR) in the top six nuclear-generating countries, Baek and Pride [36] reported that nuclear energy usage reduces CO_2 emissions. Xu [10] found that nuclear energy produces less CO_2 emissions than coal power even when used with carbon capture and storage (CCS) technologies.

The second group of researchers has contrary findings. For instance, Jin and Kim [12] investigated the relationship between CO_2 emissions and nuclear energy for 30 countries over the time span of 1990–2014. The results indicated that nuclear energy has no role in CO_2 emissions reduction. Saidi and Mbarek [37] studied the causal relationship among nuclear energy consumption and CO_2 emissions for nine developed countries for data spanning from 1990 to 2013 and found effect of nuclear energy on CO_2 emissions is insignificant. Al-mulali [38] reported mixed results for a panel of 30 major nuclear energy-consuming countries while exploring energy-emission nexus from 1990 to 2010, nuclear energy behaves contrary among under-considered countries. For the overall panel results, the coefficient of nuclear energy was positive but insignificant. Negative results are reported by Iwata [39] for 11 OECD countries and Alam [40] for a panel of 25 countries. Jin and Kim [12] found mixed results for a panel of 30 countries.

Jaforullah [41] found that that nuclear energy consumption increase CO_2 emissions whereas, Baek [42] reported the negative role of nuclear energy in carbon emission Ishida [43] reported nuclear energy consumption increases CO_2 emissions in Japan using ARDL method and Iwata [44] found that nuclear energy decrease carbon emission in France. The empirical findings by Sarkodie [45] in South Africa showed that nuclear energy promotes environmental pollution.

Form above discussion it can be summarized that previous studies have ' shown divergent results depends on the special circumstances of each country. These countries have huge financial resources, skilled labor, technologically at an advanced level, have stable economic condition and significant nuclear energy share in the total energy mix. Therefore, the outcomes of these studies are lacking the implications for developing countries. As developing countries have scare source and limited experience with nuclear energy generation. The complexity of nuclear energy generation compared to other energy sources (renewable and fossil fuels) demanded a separate investigation in resource scare developing country settings. This study focusses on the role of nuclear energy on carbon emission in context of Pakistan.

3. Material and methods

The data in the study covering the time of 45 years (1973–2017) for CO_2 emissions, economic growth and nuclear energy based on data availability. Per capita CO_2 emissions for the study measured in metric tons, economic growth as real GDP (gross domestic product) per capita taken (constant 2010 US dollar). Nuclear energy calculated in metric tons per capita. The data on nuclear energy is borrowed from BP statistical review [7], whereas the data on real GDP and CO_2 emissions are were taken from databank of world development indicators (WDI) [46].

The empirical model of the current investigation is adapted from recent studies [3,47] to examine the relationship between nuclear energy, economic growth, and CO_2 emissions and can be express as:

$$Ln(CO_2)_t = \alpha_0 + \alpha_1 LnGDP_t + \alpha_2 LnGDP_t^2 + \alpha_3 LnNE_t + \mu_0 \quad (1)$$

where CO_2 shows carbon dioxide emissions, GDP is gross domestic product and NE for nuclear energy, t represents the time period and μ is the error term. The expected sign of α_1 and α_2 are expected to be positive and negative. If $\alpha_1 > 0$ and $\alpha_2 < 0$, then it confirms the presence of the EKC hypothesis. The EKC hypothesis assumes an inverted relationship between environmental pollution and income level. At the earlier stage in the economic development, pollution rises with income increase. However, after income cross threshold level, the pollution reduces.

Literature suggests various econometric tools for long and short-run estimation. The autoregressive distributed lag (ARDL) bounds testing approach is preferred suggestion [48]. The choice of the ARDL method is corrborated that this method is capable of estimating long run and short-run dynamics at once through simple linear transformation, irrespective integration order either I(0) or I(1). Second, the ARDL is most suitable for small data sample, and handles data generating process in a general-to-specific and offer enough legs. Third, ARDL approach minimize the issues associated with non-stationary time series data. Finally, as per the statistical point of view, the specifications of the ARDL are equal to the standard error correction model. Nevertheless, standard errors it offers are expected to be different. Therefore, the estimates generated through ARDL are unbiased and reliable enough to use for policy purpose. The estimated ARDL model can be express in the following way;

$$\Delta LogCO_{2t} = \alpha_0 + \alpha_1 LogGDP_{t-1} + \alpha_2 LogGDP_{t-1}^2 + \alpha_3 LogNE_{t-1} + \sum_{k=1}^{p} \alpha_p \Delta LogGDP_{t-k} + \sum_{k=0}^{q} \alpha_q \Delta LogGDP_{t-k}^2 + \sum_{k=0}^{r} \alpha_r \Delta LogNE_{t-k} + \mu_t \quad (4)$$

where Δ is the first difference operator; $\alpha_{1,2,3}$ shows long-run coefficients, and $\alpha_{p,q,r,}$ are short-run coefficients. α_0 is a constant term and μ noise error term. The application of the ARDL procedure lies in the following steps. The first step is to choose the appropriate criteria for lag length selection. The Akaike Information Criteria (AIC) employed for the selection. The second step is to test the null hypothesis such as H_0: $\alpha_1 \neq \alpha_2 \neq \alpha_3 \neq 0$ is to be tested against H_1: $\alpha_1 = \alpha_2 = \alpha_3 = 0$. The cointegration existence decision is made on the basis of F-statistics value. For the critical F-value [48,49], introduced lower and upper bound critical values criteria employed respectively. The higher F-value than upper bound lead towards the rejection of the null hypothesis and confirms the cointegration among variables. The results are inconclusive if the F-value lies between the upper and lower bound values. To confirm the reliability and validity of the estimated results, several diagnostic tests are employed for robustness checks.

The presence of a long-run relationship can be more elaborated and understandable for policy purposes by identifying the direction of causality among study's variables. If variables are cointegrated, then there should be at least one-way causality between examined variables. So, the present study employed the VECM (vector error correction model) Granger causality approach to inspecting the causal relationship among the studied variables. The procedure of VECM test comprises several steps. It started with estimation of simple regression by getting the error correction model (ECM). If ECM value is negative and significant, we proceed further evaluations by including the ECM in the model. Wald statistics framework employed to make estimations of short-run and long-run causal relationships among the interested variables. The empirical equation of VECM Granger causality can be expressed as:

$$\begin{bmatrix} \Delta LogCO_{2t} \\ \Delta LogGDP_t \\ \Delta LogNE_t \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix} + \begin{bmatrix} \lambda_{11,1} & \lambda_{12,1} & \lambda_{13,1} \\ \lambda_{21,1} & \lambda_{22,1} & \lambda_{23,1} \\ \lambda_{31,1} & \lambda_{32,1} & \lambda_{33,1} \end{bmatrix} \times \begin{bmatrix} \Delta Log(CO_2)_{t-1} \\ \Delta Log(GDP)_{t-1} \\ \Delta Log(NE)_{t-1} \end{bmatrix} + \sum_{i=1}^{p-1} \begin{bmatrix} \beta_{11,i} & \beta_{12,i} & \beta_{13,i} \\ \beta_{21,i} & \beta_{22,i} & \beta_{23,i} \\ \beta_{31,i} & \beta_{32,i} & \beta_{33,i} \end{bmatrix} \times \begin{bmatrix} \Delta Log(CO_2)_{t-1} \\ \Delta Log(GDP)_{t-1} \\ \Delta Log(NE)_{t-1} \end{bmatrix} + \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix} \times (ECT_{t-1}) + \begin{bmatrix} \mu_{1t} \\ \mu_{2t} \\ \mu_{3t} \end{bmatrix} \quad (5)$$

4. Empirical results

4.1. Unit root test results

To obtain unbiased and reliable results, it is essential that the series should be stationary. The stationarity of the series checked through unit-root analysis. It is also a pre-requisite to apply ARDL technique. For this purpose, Augmented Ducky Fuller, Phillips Pesaran, and DF-GLD tests are applied. The reason behind using three tests is to ensure the estimated results. The results of all three

Table 1
Results of ADF, PP and DF-GLS unit root tests.

Variables	ADF test statistic		PP test statistic		DF-GLS test statistic	
	Level	First Difference	Level	First Difference	Level	First Difference
Log CO_2	−1.0489 (0.7270)	−4.1846* (0.0020)	−1.3715 (0.5875)	−4.1683* (0.0021)	0.6090 (0.5458)	−4.0236 *(0.0002)
Log GDP	−0.9998 (0.7450)	−4.8122* (0.0003)	−0.8038 (0.8081)	−4.7756* (0.0003)	0.7495 (0.4578)	−4.4987* (0.0001)
Log GDP^2	−0.7133 (0.8325)	−4.7122* (0.0004)	−0.5182 (0.8778)	−4.7122* (0.0004)	0.8098 (0.4227)	−4.3964* (0.0001)
Log Nu	−4.0371 (0.0029)	−9.9512* (0.0000)	−4.0459 (0.0029)	−10.457* (0.0000)	−3.8921 (0.0003)	−9.5161* (0.0000)

Note: * refers to rejection of null hypothesis at 1%.

Table 2
Bound testing for co-integration.

Estimated model	Optimal lag length	F-Statistics	Remarks
CO2 = f(GDP, GDP^2, NE)	1,1,1,0	5.006*	Conclusive

Note: * indicates the level of significance at 1%. For critical values please refers to Refs. [48,49].

tests are reported in Table 1. It is concluded that variables of interest are not stationary at level, and we cannot reject the null hypothesis. However, after taking the first difference, the variables become stationary such as at I(1). So, it suggested that series is stationary, and we can move further for the cointegration examination.

4.2. Results of Co-integration tests

After confirming the stationarity level of the series, the next step is to find the cointegration among considered variables. This study uses the Akaike Information Criteria (AIC) for the selection of appropriate lag length. The AIC provides efficient and reliable results in capturing dynamic relationships [18]. After appropriate lag length selection, F value is calculated which is shown in Table 2. The F-value of the bound test suggests that we can reject the null hypothesis of no cointegration which implies that there is cointegration among nuclear energy, economic growth, and CO_2 emissions.

Moreover, we have applied another test to re-check the cointegration among the variables. Bayer and Hanck (2013) can be a suitable method to investigate whether the variables are cointegrated or not. Several cointegration approaches have been proposed in the literature to analyze the long-run relationship between macroeconomic variables. This study employs [50] cointegration approach due to its additional explanatory properties. This approach not only combines the features of previous cointegration techniques [51–54] and produces F-statistics to draw efficient and comprehensive single cointegration result as well. The order of integration at I(1) is necessary to apply Bayer and Hanck technique. The estimated F-statistic beyond the critical value indicates the rejection of the null hypothesis of no cointegration. The Bayer and Hanck cointegration computed with the help of Fisher's estimated formula and expressed as follows:

$$EG-JOH = -2\left[Log(P_{EG}) + Log(P_{JOH})\right] \quad (2)$$

Table 3
Results of Bayer-Hanck cointegration test.

Estimated Model	EG-JOH	EG-JOH-BO-BDM	Decision
$LogCO_{2t}$ = f(LogGDP, LogGDP^2, LogNE)	13.8939 ***	30.315***	Cointegration

Notes: *** indicates the level of rejection at 1% level. Critical value at 1% level for EG-JOH and EG-JOH-BO-BDM are 14.782 and 32.074, respectively.

$$EG-JOH-BO-BDM = -2Log[(P_{EG}) + (P_{BO}) + (P_{BDM})] \quad (3)$$

where P_{EG}, P_{JOH}, P_{BO}, and P_{BDM} shows the probabilities of various cointegration tests such as [53,55–57] respectively. The purpose of the Fisher statistic is to see whether the cointegration exists among underlying variables.

Table 3 presents the results of the Bayer–Hanck cointegration test. The Fisher statistics for EG-JOH and EG-JOH-BO-BDM below the critical values at 1% level of significance, implies that nuclear energy and CO_2 emission co-integrated for long-run equilibrium. Thus, we cannot accept the null hypothesis of no cointegration between nuclear energy and CO_2 emissions. The results confirm the presence of cointegration. Thus, we can pursue to estimate long-run dynamics.

4.3. Estimates of a long run and short-run dynamics

For long-and short runt estimation, the ARDL approach applied. The results estimated coefficients of the long run and short run are reported in Table 4. All the variables are statistically significant in both the long- and short run. The coefficient of GDP is positive and significant, employing that CO_2 emission increases with economic growth. The coefficient of GDP^2 is negative and significant both in the long run and short run. The decreasing trend from the short run to long run indicates that there is an inverted U-shaped relationship between economic growth and CO_2 emissions, which confirms the assumption of the EKC hypothesis in the case of Pakistan.

Turning to the environmental impact of nuclear energy, according to the reported results in Table 4, the coefficient of the estimates are positive and significant both in short and long-run path. The positive association indicates that nuclear energy deteriorates environmental quality in Pakistan. These results are in line with the findings of Ishida [43] for Japan, Jaforullah [41] for the USA and Sarkodie [45] for South Africa. The negative role was also

Table 4
Results of ARDL, robust check and diagnostic test.

Variable	ARDL Long-run estimates		ARDL Short run estimates		
	Coefficient	[Prob.]	Variables	Coefficient	[Prob.]
GDP	10.696*	[0.0026]	GDP	13.021**	[0.0282]
GDP^2	−1.7056*	[0.0062]	GDP^2	−2.3019**	[0.0257]
NE	0.0635***	[0.0545]	NE	0.0141***	[0.0537]
C	16.950*	[0.0009]	CointEq(-1)	−0.222*	[0.0032]
Diagnostic tests					
R^2	0.997				
Adj. R^2	0.996				
DW	1.85				
F-value [Prob.]	1462.7	[0.000]			
$\chi2$-Reset	0.0764	[0.7839]			
$\chi2$- LM	0.6972	[0.5054]			
$\chi2$- hetero	0.0715	[0.7905]			

Note: *, ** & *** refers to rejection of null hypothesis at 1%, 5% and 10% respectively.

Table 5
Results of FMOLS, DOLS, and CCR.

Variables	FMOLS		DOLS		CCR	
	Coefficient	Prob.	Coefficient	Prob.	Coefficient	Prob.
GDP	2.537*	0.0000	1.307*	0.0000	1.396*	0.0000
GDP^2	−0.691*	0.0000	−0.404*	0.0000	−0.431*	0.0000
NE	0.814*	0.0000	0.125**	0.0347	0.124*	0.0000

Note: * refers to rejection of null hypothesis at 1%, FMOLS = Fully modified ordinary least square; DOLS = dynamic ordinary least square; CCR= Canonical Cointegration Regression.

Table 6
Results of a long run and short run causality analysis.

Short run causality Wald Statistics			Long run causality (t-statistics)	
Variables	ΔLog CO_2	ΔLog NE	ΔLog GDP	Emc_{t-1}
Log CO_2	–	1.5431 (0.1307)	−2.3845** (0.0219)	−0.1547** (0.0298)
Log NE	0.3774 (0.7078)	–	1.0003 (0.3231)	−0.5744* (0.0007)
Log GDP	1.1752 (.2468)	−2.4630** (0.0182)	–	0.0449 (0.4708)

Note: Value in parenthesis shows the probabilities values.
* indicates the level of rejection at 1%.
** indicates the level of rejection at 5%.

reported by other scholars [12,38,58]. It is worth mentioning that the elasticity of the long run is higher than that of the short run; recommend that contribution of nuclear energy in environmental degradation will increase with the passage of time which needs to be controlled at earliest.

To confirm the stability of the model and the reliability of estimated results, we have applied several diagnostic tests for multicollinearity, autocorrelation, and heteroscedasticity (see Table 4). Results reveals that the model is free from multicollinearity, autocorrelation, and heteroscedasticity, and establishes the reliability of the model.

Further for a robust check of ARDL approach estimations, we employ alternate cointegration methods such as FMOLS, DOLS, and canonical cointegration regression (CCR). The results of the alternate model are noted down in Table 5, which recommends the inverted U-shaped relationship between income and CO_2 emissions. Further, the results also suggest the nuclear energy has a positive and significant impact on CO_2 emissions. So, the finding of FMOLS, DOLS, and CCR are similar to those who come from ARDL approach.

4.4. The VECM granger causality

The long and short-run dynamics among variables recommend the nature of the relationship; however, to give insight to policymaker to design proper and effective policy recommendations it is important to learn the direction of causality among under consideration variables. The causal relationship investigation helps policymakers and government officials to devise policies accordingly. To serve the purpose, the study uses a VECM (vector error correction model) Granger causality approach. The results of the VECM are illustrated in Table 6. According to the results long-run bidirectional causal relationship exists between economic growth and CO_2 emissions, between economic growth and nuclear energy. This indicates that economic growth depends on energy growth and will affect the environment. Interestingly, nuclear energy and CO_2 emissions also have bidirectional causality. Furthermore, in the short run, economic growth Granger-causes CO_2 emissions; finally, bidirectional causality found between nuclear energy and economic growth. The results provide important insight into the direction of policymaking. The findings infer that economic growth is not the only factor to be controlled for CO_2 emissions mitigation. Moreover, rapidly increasing energy demand and existing arrangements of energy generation demand policy level shifts. Thus, presently, it is difficult for Pakistan to decouple CO_2 emissions.

5. Discussion

The estimation results confirm the EKC hypothesis for the case of nuclear energy consumption in Pakistan. From the results, it can be inferred that the benefits of economic growth for mitigating CO_2 emissions will be achieved over time. Specifically, at the initial stage of economic development, the impact of economic growth on pollution is positive, but after reaching a certain income level it will start to change in favor of environmental mitigation. This could be attributed that reaching a certain income level; people will be more aware of the clean environment and consume more energy-efficient goods. The awareness about harmful effects will result in clean environment demand, which will compel the government to regulate and implement environmental policies more effectively. Moreover, Pakistan is not an industrial economy and economic growth driven by other sectors such as agriculture and services sector. -It's therefore recommended that agrarian economies such as Pakistan should adopt sustainable agriculture practices and technological advancement and scientific innovations will be helpful to reduce further environmental deterioration. These conclusions coincide with Danish [2] for Pakistan; Dong [3] for China, Lau [35] for OECD countries, and Sina [59] for India.

Considering the role of nuclear energy in CO_2 emissions reduction, the coefficient of nuclear energy has a positive sign. It means nuclear energy accelerates CO_2 emissions in Pakistan. Thus, the findings of our study deviate from existing studies about nuclear energy as a clean energy source which was endorsed by many scholars [9,10,39,60−62]. This deviation to common perception can be explained for different arguments. The low quantitative share of nuclear energy (4.36%) in the total energy mix of Pakistan [63]. As nuclear energy required to cross the threshold level to mitigate carbon emissions [58,61]. Similar finding was also reported for renewable energy with low share [25]. Another reason may be that nuclear energy utilized to meet essential energy requirements, and it doesn't displace existing carbon-emitting fossil fuel generation. In the absence of displacement affect, it resulted in environmental deterioration [64].

The smaller capacity nuclear power plants (such as 10 MWe, 137 MWe, and 340MWe) may be the other factor form negative role of nuclear energy in environmental pollution. Nuclear power plant construction requires massive infrastructural development. Although nuclear power plants do not emit CO_2 emissions directly, the infrastructural carbon footprints are greater than their environmental benefits, especially for small facilities that cause CO_2 emissions. So it demands a comprehensive life cycle assessment of a nuclear power plant while considering the specific circumstance of operating territory before starting a nuclear program. Maybe the infrastructural and operating requirements offset their intended environmental benefits. According to the preliminary planning by IAEA and PAEC (Pakistan Atomic Energy Commission) in 1975 at the start of nuclear energy program, Pakistan was supposed to produce around 16000 MWe by nuclear power up to 60% of total electricity till 2000. The nuclear energy growth was planned with higher capacity nuclear reactors such as eight power reactors of 600MWe between 1982-1990. The subsequent addition from 1991 to 2000 was planned with nine power reactors of 600MWe and seven reactors of 800MWe capacity. Pakistan not only deviates from its initial planning but even faced restrictions by the international community to operate already developed facilities [65,66]. These restrictions and non-cooperation resulted in negative effects the environment.

The positive association among nuclear energy and GDP may be attributed to the dual role of nuclear energy by solving the problem of electricity shortage to some extent and responsible for the growth of the related and supported industry providing facilities for nuclear energy development. As Pakistan is in continuous process of nuclear energy infrastructural development program for the last three decades [67] and increased economic activity in the country but cost of the detrimental effects on the environment.

Nuclear waste management is another important aspect of nuclear energy generation. Due to technical incompetence and other restrictions by the international community, Pakistan mostly relies on indigenous resources to operate nuclear power plants. This resulted in more radioactive waste, which has more irreversible grave effects on humanity and for the environment as well [12,45]. It is supposed to have special infrastructural and processing arrangements to handle nuclear waste. The globally accepted practice and standards to dispose of this waste for long term basis in dry storage facilities. In dry facility nuclear waste stored in compacted steel mild drums and reinforced cemented concrete under the ground. But Pakistan has no dry storage facility for nuclear waste management, contrary relying on the wet storage system nuclear waste stored on-site fuel pools [68].

The other possible reason may be the operational inefficiency. As all nuclear power plants are operated with a single government-owned organization which lacking performance and transparency measures, absence of strong and independent regulator for monitoring and evaluations measures, resulted in opposite outcomes. The present study negative results demanded for environmental efficiency, a transparent examination and evaluation of existing as well as under-construction nuclear projects. The other reason may be the excess storage of sealed radioactive sources in the country for environmental pollution [68]. These results are in line with the findings of [38] that nuclear energy consumption has a positive effect on CO_2 emissions, especially in developing countries. Such findings were also endorsed by other scholars [12,39,40]. Even the negative behavior was found in advance economies by Ishida [43] for Japan and Jaforullah [41] for the USA. Menyah [69] found a similar relationship for renewable energy consumption for the USA. Relate to the extent of literature, most studies agree with positive role of nuclear energy in environmental pollution mitigation. It means that nuclear energy can behave as clean source in Pakistan if some effective measures are taken.

6. Conclusion

The study aimed to investigate the role of nuclear energy in carbon emission for Pakistan by taking longest available data span from 1973 to 2017, employing autoregressive distributed lag (ARDL), model. From the finding, we can infer that currently nuclear energy contributing to environmental pollution. Apart from it, nuclear energy helps to form an inverted U-shaped relationship between economic growth and CO_2 emissions. Besides, unidirectional causality is running from CO_2 emissions to economic growth and from economic growth to nuclear energy.

The findings directed toward essential policy recommendations. Improvement in infrastructure for nuclear generation should be initiated at earliest. An independent regulatory body is required for better performance to achieve the threshold level of nuclear energy share and to build nuclear waste management facilities. The operational performance, efficiency, and monitoring checks are necessary to ensure environmental quality. Further research and development in nuclear energy, is suggested to make nuclear energy a clean source of energy in Pakistan. This study comes with special recommendations for resource-scarce countries like Pakistan before starting a nuclear power program. As it requires huge long-term investment and commitment by the government, capable human resource and institution infrastructure. Moreover, nuclear energy generation demands special safety, security, and safeguard measures because of its serious irreversible consequences to humanity and the environment.

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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