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Exploring Nuclear Energy and Environment Interaction in Pakistan Using the Fourier ARDL

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Abstract
This research examines the relationship between nuclear energy and environmental quality in Pakistan from 1971-2020 with the help of Fourier ARDL. In 2020, the use of fossil fuels, CO_2 emissions, and the population had increased by 203.02%, 211.61%, and 101.18%, respectively, compared to 1990. This rise in contamination has caused a strain on the air quality in the country. To mitigate this, the use of nuclear energy increased from 0.18% in 1990 to 2.34% in 2020. The findings suggest that nuclear energy could be an effective policy for Pakistan if they want to improve its environmental quality. Additionally, it is projected that the detrimental externalities linked to pollution can be minimized in a year. Furthermore, with a 318% rise in energy imports in 2020 compared to 1990, it is vital for Pakistan to responsibly raise its utilization of nuclear energy to lessen its dependence on foreign energy sources and promote environmental quality. The economic repercussions of nuclear energy use in Pakistan are controversial; some studies suggest this increased usage might be impeding economic growth, while other studies suggest the opposite. This analysis seeks to examine the link between nuclear energy production and environmental damage using an appropriate method and scope.

Keywords
Nuclear energy, CO_2 emissions, Fourier ARDL, Pakistan.

Introduction

With globalization, the free movement of capital has increased, leading to high growth figures in economies (Awad, 2023; Azad, 2023; Bulatov, 2023). Increasing high growth rates have increased the energy demand (Yu et al., 2023; Xu et al., 2023). The reliance on fossil fuels to meet the growing energy demands worldwide is resulting in climate change and irreversible environmental damage. This is due to the large portion of fossil fuels in the overall energy consumption (Hossain et al., 2023; Tanwer et al., 2023). While the share of fossil fuels in the world's total energy use was 81.43% (coal 25.41%, oil 36.99%, and natural gas 19.03%) in 1990, this share was 80.88% (coal 26.77%, oil 30.89%, and natural gas 23.21%) in 2019 (IEA, 2023). This situation caused global CO_2 emissions to increase by 63.92% in 2019 compared to 1990.

The annual average growth rate of 3.01% and 1.30%, respectively, in global GDP and global population from 1990-2019 causes an increase in energy demand (World Bank, 2023). On the other hand, global fossil fuel use and global CO_2 emissions increased on average by 1.74% and 1.72% annually from 1990-2019, respectively (IEA, 2023). Therefore, the fact that the share of fossil fuels has such a high share shows that fossil energy cannot be easily abandoned soon. In addition, fossil fuel dependence, which will continue for a long time, shows that environmental degradation will increase for many years(Hou et al., 2023; Ağbulut et al., 2023).

In addition, the COVID-19 global pandemic has exacerbated the already-existing need for a healthier and cleaner World (Whitsel et al., 2023; Bhattacharya and Bose, 2023). Hence, high fossil fuel dependency shows that a more livable world will be discussed for many years (McCauley et al., 2023). The reason for this is that the energy demand is increasing every year, and the need to meet this demand with clean energy is increasing (Berndes et al.,2003; Matsuo et al., 2013; Gielen et al., 2019; Akimoto et al., 2022). Alternative energy sources are needed to reduce CO_2 emissions. Among the most important ones is increasing the use of renewable energy (Ehigiamusoe and Dogan, 2022; Kirikkaleli et al., 2022; Yu et al., 2022). On the other hand, the use of nuclear energy is among the important alternative energy sources compared to fossil energy (Pata and Samour, 2022; Sadiq et al., 2022, Murshed et al., 2022; Fell et al., 2022).

Nuclear energy is an important alternative energy source that requires serious responsibility to improve environmental quality. However, nuclear energy is a clean energy source compared to fossil fuel energy, and it is an energy for which there are many concerns about increasing its use (Wejnert and Wejnert-Depue, 2023). Among the most important reasons for this is that, first of all, there should be important safety problems and serious responsibilities for the use of nuclear energy (Meserve, 2022; AlKaabi, 2022). Another important reason is the increasing concern that nuclear weapons may cause an increase (Humphrey and Khandaker, 2018; Suman, 2018). Finally, they are the great difficulties encountered during the disposal of radioactive waste (Ramana, 2018; Wisnubroto et al., 2021). Therefore, all these reasons cause constant concerns about the nuclear energy source being up-to-date.

However, despite these justified concerns, the use of nuclear energy is important for the Pakistan economy, which has a special position among the developing economies (Xu et al., 2023a; Hassan et al., 2023) because of the high growth of the Pakistani economy and the high energy demand brought by its increasing population. In addition, while the GDP of Pakistan's economy increased by 224.11% and its population increased by 101.18% compared to 1990, the use of fossil fuels increased by 203.02% (coal by 549.76%, oil by 105.23%, and natural gas by 237.78%). In the same period, the use of renewable energy, on the other hand, increased by 84.84%, well below the desired level and slightly. On the other hand, nuclear energy has been the energy source with the highest increase rate, with an annual average increase of 12.95% in the 1990-2019 period (IEA, 2023).

This study investigates the relationship between nuclear energy and CO_2 emissions for the Pakistani economy, which increased its nuclear energy use by 3315.74% in 2019 compared to 1990. At the same time, the validity of the EKC hypothesis is tested for the Pakistani economy in the relevant period. The graph of the EKC hypothesis is shown in Figure 1.

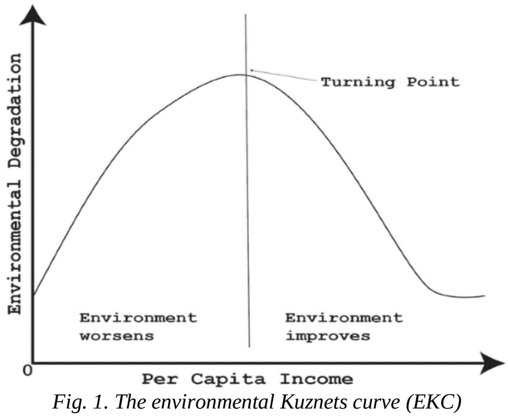


Fig. 1. The environmental Kuznets curve (EKC)

When Figure 1 is examined, it is seen that the EKC curve has a concave shape. It is seen that this curve firstly has a decreasing increasing graph. Here, the increase in income is achieved by increasing environmental degradation. In other words, dirty growth is taking place. However, this dirty growth has started to decline. Then, environmental degradation stops at the peak where the slope of the curve is zero. Then, it is seen that the EKC curve has an increasing decrease. In other words, the income increases are now realized by the rapid decrease in the deterioration of environmental quality (Freire et al., 2023; Wang et al., 2023).

This study has many contributions to the literature. For the Pakistani economy, which is primarily an energy importer, the use of renewable energy has increased by 84.84% in the last thirty years, while the use of nuclear energy has increased by 3315.74%. Therefore, the effect of cleaner nuclear energy, which can be an alternative to fossil energy for the Pakistani economy, and the highest increase in the environmental quality is investigated. In addition, during the 1990-2019 period, global CO_2 emissions had an annual average increase of 1.72%, while this increase was 3.99% in Pakistan. Hence, it is considered that the improvement in CO_2 emissions in Pakistan will reflect positively on global environmental quality. The next contribution is that few studies have examined the impact of nuclear energy use on the Pakistani economy (Mahmood et al., 2020; Majeed et al., 2022). In the studies examined, on the other hand, either a short time is covered or researched with out-of-date techniques. In this study, the Fourier ARDL method, which has been brought to the literature in the last 50 years and in recent years, is used. For the Fourier ARDL method, there is no strict requirement for the integrated levels of the variables. On the other hand, in studies where the structural changes are dummy variables, the structural changes take the values of 0 and 1, indicating a drastic structural change. However, in studies where Fourier functions are used, the structural changes are slower and softer and more compatible with real life. In addition, in studies using Fourier functions, there is no strict assumption about the number of structural changes that the model may have.

After this section, it is planned to include the relevant literature research first. Then, the introduction of the variables and the method, obtaining the findings, and finally, the conclusion and evaluation part are included.

A Brief Overview of The Literature

Despite today's technologies, fossil energy had a share of 80.88% of global energy resources in 2019. The petroleum resource, which has the highest share among fossil fuel resources, with 38.20%, continues to be the leader. However, it is followed by coal at 33.10% and natural gas at 28.70%. On the other hand, the share of total renewable energy in 2019 has a small share of 4.72% (IEA, 2023). Therefore, the share of renewable energy is still very small and remains well below the desired level. This shows that fossil energy will provide most of the increasing energy demand. The relatively low share of renewable energy use is a serious concern about the future of environmental degradation (Liu et al., 2023; Razzaq et al., 2023). Hence, nuclear energy, which can be an alternative to fossil energy and provide sustainability, offers important opportunities (Obekpa and Alola, 2023; Ağbulut et al., 2023). Therefore, many studies in the literature have wondered about and investigated the effects of nuclear energy on environmental quality. In this study, the effect of nuclear energy use on environmental quality is investigated. However, together with the nuclear energy variable, the economic growth variable was also used.

For this study, the literature was analyzed in two parts. Firstly, the effect of nuclear energy use on environmental quality was investigated, and in the other section, the relationship between economic growth and the environment was examined.

a) The Impact of Nuclear Energy on Environmental Quality

Nuclear energy is considered an important alternative energy source compared to fossil fuels, which produce 2 gigatons of CO_2 annually (Majeed et al., 2022). Therefore, nuclear energy is considered to offer significant opportunities to reduce carbon emissions.

There are few studies in the literature investigating the relationship between nuclear energy and environmental quality. Saidi and Omri (2020) investigated the role of nuclear energy and renewable energy use on CO_2 emissions in OECD countries from the period 1990-2018. In the study in which panel estimators were used, it was found that the use of renewable energy alone would not be sufficient to reduce CO_2 emissions. It was stated that the best option would be a mixture of nuclear energy and renewable energy. Apergis and Payne (2010) examined the relationship between nuclear energy consumption and CO_2 emissions for 19 developed and developing country groups in the 1984-2007 period using a panel error correction model. The findings have found that nuclear energy is important in reducing CO_2 emissions in the short and long term. On the other hand, Menyah and Wolde-Rufael (2010) investigated the effect of nuclear energy on environmental quality in the USA during the period 1960-2007. In the study using Granger causality, research findings showed that the use of nuclear energy in the USA can help improve environmental quality. Similarly, Chang (2010) found a causal relationship between nuclear energy consumption and CO_2 emissions in the Chinese economy from 1981-2006. Using the Granger causality test, al-Mulali (2014) investigated the relationship between nuclear energy consumption and CO_2 emissions for 30 major nuclear energy-consuming countries in the 1990-2010 period. The findings showed that the use of nuclear energy in the 30 countries that were the subject of the study did not have any effect on CO_2

emissions. However, it has been found that the increasing effect of nuclear energy use on economic growth is significant. On the other hand, Destek and Aslan (2020) have shown that energy consumption has an insignificant impact on CO_2 emissions in the G7 countries. Similarly, Khoshnevis Yazdi and Shakouri (2018) for Germany and Nathaniel et al. (2021) for MENA countries found that energy sources without carbon emissions do not affect CO_2 emissions.

Therefore, it is seen that different results are obtained between nuclear energy and CO_2 emissions in the literature. The reason for this is considered to be that the findings obtained as a result of the use of a different method(s) for a different country(s) in the studies differ.

b) The Impact of Economic Growth on Environmental Quality

The relationship between economic growth and the environment is generally based on the EKC hypothesis in the literature. It is the case where the second derivative of the model used for the EKC curve is less than zero. In this case, the curve has a decreasing increasing shape, then a stationary, and then an increasingly decreasing shape. In other words, it shows that higher growth first causes deterioration of environmental quality. This deterioration then stabilizes and then decreases rapidly. Because, after a certain point, increasing income leads to a rapid increase in environmental quality with more use of environment-oriented policies and energy-efficient technologies (Majeed et al., 2022).

In many studies in the literature, the EKC hypothesis is examined by econometric analysis using different methods, and the results differ. Some studies have found that the EKC hypothesis is valid for different countries with different methods (Song et al., 2019; Isik et al., 2020; Farhani and Balsalobre-Lorente, 2020; Cary, 2020; Khan and Hou, 2021; Abumunshar et al., 2020; Ahmad et al., 2021; Altarhouni et al.,2021; Fatima et al., 2021; Qashou et al., 2022; Pata and Yurtkuran, 2023; Aydin et al., 2023; Wang et al., 2023a; Jahanger et al., 2023). In other words, they found that there is an inverted-U-shaped relationship between economic growth and CO_2 emissions. On the other hand, in some studies, it has been found that the EKC hypothesis is not valid; that is, there is a U-shaped curvilinear image (Seppälä et al., 2001; Isik et al., 2019; Godil et al., 2020; Pata and Tanriover, 2023; Massagony and Budiono, 2023; Wang et al., 2023; Barut et al., 2023; Ben Abdeljelil et al., 2023).

Data, Methodology and Findings

In this section, the effect of nuclear energy consumption and GDP variables on CO_2 emissions for the Pakistani economy in the period 1971-2020 will be investigated. For this, the studies by Mahmood et al. (2020), Majeed et al. (2022), and Ozgur et al. (2022) are followed, and the following model is taken into account.

$$CO_{2_t} = \beta_0 + \beta_1 GDP_t + \beta_2 GDP_t^2 + \beta_3 NUCLEAR_t + \varepsilon_t \qquad (1)$$

where CO_2 refers to carbon dioxide emissions per capita (metric tons), GDP refers to per capita GDP (constant 2015 USD$), and NUCLEAR refers to per capita nuclear energy consumption (tons of oil equivalent). While the GDP data were obtained from the World Bank (2023) database, the CO_2 and NUCLEAR data were obtained from the BP statistical analysis. The natural logarithms of all series were taken. Descriptive statistics for all variables were calculated and given in Table 1

Tab. 1. Descriptive statistics of the series

	CO_2	GDP	GDP^2	NUCLEAR
Mean	-0.289	2.981	8.902	-0.815
Median	-0.227	3.003	9.017	-0.861
Maximum	-0.072	3.177	10.093	0.017
Minimum	-0.584	2.752	7.574	-1.863
Std. Dev.	0.162	0.126	0.746	0.482
Skewness	-0.452	-0.320	-0.263	-0.172
Kurtosis	1.780	2.004	1.982	2.363
Jarque-Bera	4.807	2.919	2.734	1.090
Probability	0.090	0.232	0.255	0.580
Observations	50	50	50	50

According to Table 1, when the sizes of the series are compared, it is seen that the series with the maximum average is economic growth GDP2, while the series with the minimum average is NUCLEAR. On the other hand, the series with the highest volatility was found to be GDP2, while the series with the least volatility was found to be CO_2. In addition, Skewness and Kurtosis values give clues about the normal distribution of the series. On the other hand, considering the Jarque-Bera Test statistic and probability values, the basic hypothesis that it has a normal distribution cannot be rejected. Therefore, it exhibits a normal distribution.

a) *Standard* ADF *and Fourier ADF Stability Tests*

In this section, the stationarity test will be done for the variables. First, the standard ADF stationarity test will be used. Structural changes are not taken into account when using the standard ADF stationarity test. This may reduce the next method to be used and the reliability of the results. The reason for this is that if the standard ADF stationarity test is used, a series of structural changes that include structural changes are not taken into account, so stationarity can be encountered. For this reason, the use of tests in which structural changes are taken into account will increase the reliability of the test results.

Therefore, in the literature, stability tests have begun to be developed in which structural changes are taken into account. Structural breaks are taken into account in the stationarity test, which was introduced to the literature by (Enders and Lee, 2012). For this, testing is done with low-frequency trigonometric functions. This test can also deal with issues related to the amount and time of structural change of the series. Because the Fourier ADF test developed by (Enders and Lee, 2012) is obtained by adding sine and cosine functions to the model. They stated that structural changes can be captured in this way and that the important thing here is to determine the frequency.

Below is the standard ADF equation:

$$\Delta y_t = py_{t-1} + \beta_1 + \beta_2 trendu_t \quad (2)$$

Enders and Lee (2012) included the sine and cosine trigonometric functions in the model and obtained the following model:

$$\Delta y_t = py_{t-1} + \beta_1 + \beta_2 trend + \beta_3 \sin\left(\frac{2\pi kt}{T}\right) + \beta_4 \cos\left(\frac{2\pi kt}{T}\right) + u_t \quad (3)$$

Where *t* is the trend, *T* is the time, and *k* is the frequency to be determined. In addition, while determining the frequency value, the frequency value obtained for the minimum value of the residual sum of squares (MinSSR) will be used. Therefore, by determining the MinSSR value, the appropriate frequency value can be obtained.

Standard ADF and Fourier ADF stability tests were applied to the series, and the results are shown in Table 2.

Tab. 2: Standard ADF and Fourier ADF Unit Root Test Results

Level	**ADF**	**F-ADF**	**F-Test**	**Frequency**	**MİNSSR**	**Lag**
CO_2	-2.5044	-2.737356	2.498054	4	0.014491	1
GDP	-2.9046*	-3.063091	2.644671	4	0.002704	8
GDP^2	-2.6066*	-2.885755	2.512124	4	0.095415	8
NEC	0.6268	-3.514614	4.982144	1	2.463973	1
1st Dif.	**ADF**	**F-ADF**	**F-Test**	**Frequency**	**MİNSSR**	**Lag**
ΔCO_2	-3.3541**	-3.924713	1.857661	5	0.006471	1
ΔGDP	-2.0628	-3.047786	3.627650	4	0.002748	1
ΔGDP^2	-3.8273***	-3.126934	3.748117	4	0.095424	1
ΔNEC	-4.7053***	-6.529812	4.199360	5	2.690229	1

Note: Critical values for the F test are 1%=10.35%, 5%=7.58, 10%=6.35%, Fourier ADF critical values for *k*=1 are 1%=-4.42%, 5%=-3.81, 10%=-3.49%, critical values for the standard ADF test are 1%=-3.753, 5%=-2.998, 10%=-2.639. ***, ** and * values indicate that the series are stationary at 1%, 5% and 10% significance levels, respectively.

When Table 2 is examined, since the F test statistic for all variables is found to be less than the critical values, the Standard ADF test results for the series will be interpreted. While CO_2 and NUCLEAR variables have unit root at level values, GDP2 and GDP variables are stationary at a 10% significance level. On the other hand, when the first difference of all variables is taken, it is seen that excluding the GDP variable, CO_2 is stationary at a 5% significance level, while GDP2 and NUCLEAR variables are stationary at a 1% significance level.

b) Fourier ARDL Bootstrap Cointegration Test

The Fourier ARDL test will be used for the relationship between the variables. There are many advantages to using the Fourier function. Most importantly, in econometric methods where structural changes are included in the model as dummy variables, the breaks have a sharp break because dummy variables in the form of 0 and 1 are added. However, in real life, structural changes do not occur suddenly but gradually and slowly. Therefore, the Fourier functions take these breaks and changes into account with smooth transitions due to the nature of the graphs they have. Hence, the results obtained from the Fourier functions are the results that are more realistic in real life. On the other hand, there are no prerequisites for the integration levels of the variables for the Fourier ARDL (Ozgur et al., 2022).

In order to examine the effect of nuclear energy on CO_2 emissions, the economic growth variable is added to the model as a control variable. While testing the EKC hypothesis, the slope coefficients for the GDP^2 and GDP variables included in the model are expected to be statistically significant. If it is significant, since the EKC curve does not start from the origin, it is expected to be $\beta_1>0$, not $\beta_1=0$. In addition, $\beta_2>0$ is expected for the validity of the EKC hypothesis.

F and *t* statistics are used for the ARDL approach introduced by Pesaran et al. (2001) to the literature. The long-term relationship is tested by comparing the obtained test statistics with the lower and upper limits. Pesaran et al. The ARDL model proposed by Pesaran et al. (2001) is given below:

$$\Delta CO_{2_t} = \beta_0 + \beta_1 CO_{2_{t-1}} + \beta_2 GDP_{t-1} + \beta_3 GDP_{t-1}^2 + \beta_4 NEC_{t-1} + \sum_{i=1}^{p-1} \vartheta_i{}' \Delta CO_{2_{t-i}} + \sum_{i=1}^{p-1} \theta_i{}' \Delta GDP_{t-i} + \sum_{i=1}^{p-1} \pi_i{}' \Delta GDP_{t-1}^2 + \sum_{i=1}^{p-1} \mu_i{}' \Delta NEC_{t-i} + e_t \quad (4)$$

Where, Δ is the difference operator, *p* is the lag length, and e_t is the error term. Given that the test statistic obtained here is between the lower and upper limits, it is not sufficient to determine the existence of a long-term relationship. Therefore, Mcnown et al. (2018), as a complement to the test, the basic hypothesis $\beta_2=\beta_3=0$ is tested.

Structural changes that the series may have may affect the results obtained when performing time series analysis. For this reason, structural changes should be included in the models for the reliability of the results obtained. The number of methods using Fourier functions, which have been brought to the literature in recent years, is increasing. Fourier functions were added to the ARDL model proposed by (Mcnown et al., 2018). Yilanci et al. (2020) stated that the results could be obtained more reliably with the Fourier functions added. The added Fourier functions are as follows:

$$d(t) = \sum_{k=1}^{n} a_k \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{n} b_k \cos\left(\frac{2\pi kt}{T}\right) \quad (5)$$

Where, π is the number of 3.14 used in mathematics, *t* is the trend, *T* is the time, and *n* is the frequency. Hence, The Fourier ARDL model proposed by Yilanci et al. (2020) is as follows:

$$\Delta CO_{2_t} = \beta_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \beta_1 CO_{2_{t-1}} + \beta_2 GDP_{t-1} + \beta_3 GDP_{t-1}^2 + \beta_4 NEC_{t-1}$$

$$+ \sum_{i=1}^{p-1} \vartheta_i{}' \Delta CO2_{t-i} + \sum_{i=1}^{p-1} \theta_i{}' \Delta GDP_{t-i} + \sum_{i=1}^{p-1} \pi_i{}' \Delta GDP_{t-1}^2 + \sum_{i=1}^{p-1} \mu_i{}' \Delta NEC_{t-i} + e_t \quad (6)$$

In this model, similar processes were followed in the studies conducted by (Yilanci et al.,2020; Christopoulos and Leon-Ledesma, 2011; Omay, 2015). Appropriate frequency values expressing the minimum residual squares were determined as *k*=0,1,…,5. In addition, the critical values of F_A, F_B, and *t* there are obtained by Bootstrap (Yilanci et al.,2020).

The Fourier ARDL test was used for the long-term relationship between the variables, and the results are given in Table 3.

Tab. 3. Cointegration Results

Dep. Var.	***Frequency***	***Min AIC***	***Lag***		***statistics***	***Bootstrap Critical Values***		
						%1	***%5***	***%10***
CO_2	1	-6.957135	2-0-1-0	F_A	7.521497**	8.986703	7.008192	6.081645
				F_B	-5.154009**	-5.474171	-4.704676	-4.297016
				t	9.942439***	8.380129	6.059401	4.948013

Note: *** and ** values are 1% and 5% significance levels, respectively. 5000 simulations were performed while obtaining critical values.

If we pay attention to Table 3, the F_A, F_B, and *t*-test statistics are absolute values greater than the critical values obtained by Bootstrap. Therefore, the basic hypothesis that there is no cointegration between the variables is rejected. Hence, there is a long-term relationship between the explanatory variables and the dependent variable in the relevant period. The cointegration estimation will be made for the size and direction of this relationship. However, some diagnostic tests were performed for the model before the long-short-term estimation.
Diagnostic tests were performed for the ARDL Model, and the results are given in Table 4.

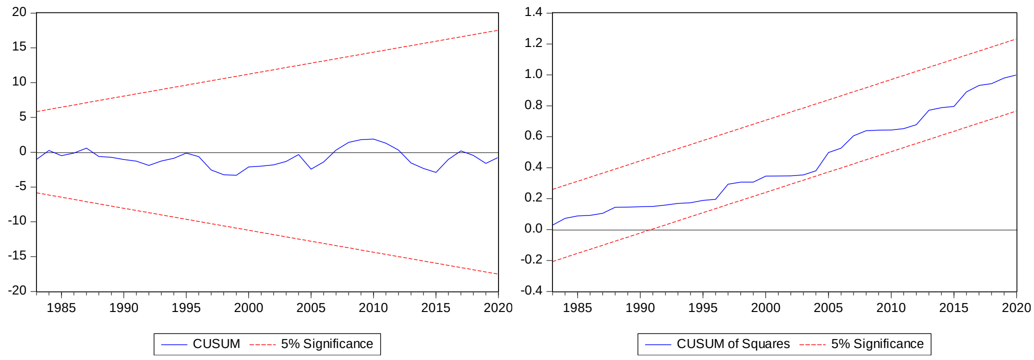
Tab. 4. Diagnostic Tests

Tests	**Statistics**
Jarque Bera [Prob.]	0.791 [0.673]
Breusch-Godfrey [Prob.]	0.877 [0.645]
White [Prob.]	37.357 [0.361]

When Table 4 is examined, it is seen that there is no heterocesdacity problem in the ARDL model according to the White test, and there is no autocorrelation problem according to the Breusch-Godfrey test. In addition, Jarque Bera test results show that it has a normal distribution.

The goodness of fit measurements was made for the ARDL model, and the obtained CUSUM and CUSUM2 results are given in Graphic 1.

Graph. 1. Stability Tests



According to Graphic 1, the ARDL model has very high goodness-of-fit criteria, and the chart results show the high stability of the model.

Long-short-term estimation results based on the Fourier ARDL model were estimated, and the results are given in Table 5.

Tab. 5. Long-Run Coefficient Results

Dep. Var.	***GDP***	***GDP^2***	***NEC***	***C***
CO_2	*1.676*** (0.290)*	*-8.809*** (1.719)*	*-0.015*** (0.005)*	*11.042*** (2.540)*

Note: The values ***, ** and * are 1%, 5% and 10% significance levels, respectively. Values in parentheses are standard error values.

When Table 5 is examined, it is seen that all coefficients are statistically significant at the 1% significance level in the long term. According to the model results, the coefficient of GDP is positive. In other words, higher growth causes higher CO_2 emissions. However, the coefficient of GDP2 has a negative value in the long run. This shows that the EKC hypothesis is valid for the Pakistani economy in the relevant period. Therefore, the curve has an inverted U-shaped appearance due to the negative coefficient of GDP2. Hence, the theoretical expectations valid for the EKC hypothesis are valid for the Pakistani economy. In other words, the ever-increasing income for the Pakistani economy shows that it has different effects on CO_2 emissions. In other words, the increase in income primarily causes environmental degradation. Then it remains constant and then causes a reduction in environmental degradation.

According to the model results, although the increase in the use of nuclear energy is small, it is seen that it has a reducing effect on CO_2 emissions. When analyzed as a coefficient, a 1% increase in the use of nuclear energy creates an approximately 0.02% decrease in CO_2 emissions. Nuclear energy is a clean energy source for the Pakistani economy in terms of energy security and sustainable energy. However, these results suggest that nuclear energy should be increased, but it cannot be very successful on its own. Therefore, these results show that green energy investments should be increased along with nuclear energy policymakers. Empirical findings support the view that the use of responsible and safety-enhanced nuclear energy should be increased.

The short-term effect of nuclear energy use on CO_2 emissions has been calculated and concluded in Table 6.

Tab. 6. Short-Run Coefficient Results

Dep. Var.	***$\Delta CO_2(-1)$***	***ΔGDP^2***	***SIN***	***COS***	***ECT***
ΔCO_2	*0.180*** (0.054)*	*1.290*** (0.127)*	*-0.026*** (0.004)*	*-0.044*** (0.005)*	*-0.806*** (0.089)*

Note: ***, ** and * values indicate that the series are stationary at 1%, 5% and 10% significance levels, respectively.

When Table 6 is examined, the ECT coefficient was found to be negative, significant, and in the range of (-1.0) by the theoretical expectation. Therefore, the existence of a long-term relationship between the variables has been verified, and the error correction mechanism is working. The ECT coefficient (-0.806) indicates that approximately 81% of the deviations in environmental quality will be corrected and stabilized within one year.

When the variables are examined, the use of nuclear energy for the Pakistani economy in the long term is an important alternative tool to fossil energy to increase environmental quality and energy independence. However, nuclear energy investments should be made considering the risks of nuclear energy.

Conclusion and Policy Implications

Despite today's technologies, the share of fossil fuels in total energy use is still very high, and the share of renewable energy is very low. This means that most of the increasing energy demand will be met by fossil fuels. The increasing use of fossil fuels causes great damage to the environment. The low level of renewable energy alone is insufficient to improve environmental quality. For this reason, the need for cleaner alternative energy sources has started to increase along with renewable energy to reduce global CO_2 emissions. On the other hand, nuclear energy is a cleaner energy source than fossil fuels in the fight against environmental destruction. However, there are many concerns about the safety of nuclear energy. Despite these concerns, nuclear energy is used by many economies as reliable and sustainable energy.

In this study, the effect of nuclear energy use on CO_2 emissions for the Pakistani economy in the period 1971-2020 is investigated. For the Pakistani economy, which has a high economic and social potential, the use of nuclear energy has been the fastest-growing energy source in the last three decades. Therefore, the magnitude and direction of the effect of this energy source on CO_2 emissions have been investigated. The Fourier ARDL method, which includes fourier functions that can better capture soft and gradual processes, was used as a method. According to the Fourier ARDL test results, explanatory variables and CO_2 emissions act together in the long run. According to the estimation results for the magnitude and direction of the effect of explanatory variables on CO_2 emissions, the GDP variable has a high positive value. However, the GDP^2 value was found to have a much higher negative value. This shows that the EKC hypothesis is valid for the Pakistani economy. On the other hand, according to the long-term model results, the increase in nuclear energy consumption shows that it reduces CO_2 emissions. This shows that nuclear energy offers significant opportunities for sustainable growth and reliable energy supply.

According to the long-term model results, nuclear energy is a clean energy source. However, this alone is not enough for environmental sustainability. Consequently, higher investments in nuclear energy are important. In addition, environmental-oriented energy investments are also necessary to reduce environmental degradation. On the other hand, in the short term, the fact that the ECT coefficient is compatible with the theoretical expectation indicates that the environmental deterioration in the Pakistani economy will be corrected within a year. Therefore, these results show that energy policies are effective for the Pakistani economy.

As a result, the use of nuclear energy reduces CO_2 emissions in Pakistan. Therefore, policymakers have important duties for the Pakistani economy. First, it is necessary to increase investments and incentives in nuclear energy to reduce foreign dependency on energy and promote a reliable energy supply. Therefore, increased use of nuclear energy will result in less foreign exchange requirement, less current account deficit, and a less fragile economy for Pakistan's economy. In addition, it would be beneficial to take rigorous and responsible security measures at nuclear power plants to ensure the safe use of nuclear energy. On the other hand, policies to facilitate the growth of renewable energy sources, such as subsidies and tax credits, are essential to reduce global CO_2 emissions.

Future studies may focus on the impact of renewable energy on CO_2 emissions alongside nuclear energy. In addition, the research of the EKC hypothesis in different country groups on the basis of the sector will also contain more detailed information.

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