Nuclear Engineering and Technology 54 (2022) 1657–1663

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

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

Original Article

Nuclear energy consumption and CO_2 emissions in India: Evidence from Fourier ARDL bounds test approach

Onder Ozgur [a,*], Veli Yilanci [b], Maxwell Kongkuah [c]

[a] Faculty of Political Sciences, Department of Economics, Ankara Yıldırım Beyazıt University, Esenboğa Campus, Çubuk, Ankara, Turkey
[b] Faculty of Political Sciences, Department of Economics, Canakkale Onsekiz Mart University, Terzioglu Yerleskesi Merkez, Canakkale, Turkey
[c] School of Finance and Economics, Jiangsu University, 301 Xuefu Road, Zhenjiang, China

ARTICLE INFO

Article history:
Received 27 June 2021
Received in revised form
27 October 2021
Accepted 2 November 2021
Available online 5 November 2021

Keywords:
Nuclear energy
CO_2 emissions
Fourier ARDL
India

ABSTRACT

This study uses data from 1970 to 2016 to analyze the effect of nuclear energy use on CO_2 emissions and attempts to validate the EKC hypothesis using the Fourier Autoregressive Distributive Lag model in India for the first time. Because of India's rapidly rising population, the environment is being severely strained. However, with 22 operational nuclear reactors, India boasts tremendous nuclear energy potential to cut down on CO_2 emissions. The EKC is validated in India as the significant coefficients of GDP and GDP.[2] The short-run estimates also suggest that most environmental externalities are corrected within a year. Given the findings, some policy recommendations abound. The negative statistically significant coefficient of nuclear energy consumption is an indication that nuclear power expansion is essential to achieving clean and sustainable growth as a policy goal. Also, policymakers should enact new environmental laws that support the expansion and responsible use of nuclear energy as it is cleaner than fossil fuels and reduces the cost and over-dependence on oil, which ultimately leads to higher economic growth in the long run. Future research should consider studying the nonlinearities in the nuclear energy-CO_2 emissions nexus as the current study is examined in the linear sense.

1. Introduction

Energy usage has increased exponentially in the modern era as opposed to prior eras. Fossil fuel-based energy production contributes mainly to carbon dioxide or greenhouse gas (GHG) emissions. In recent years, CO_2 emissions have increased significantly and are expected to continue to climb in the coming years [1,2]. There has been a protracted and ongoing debate over mitigating global warming and reducing CO_2 emissions. Given that global energy consumption is sure to expand over time [3–5], and given the relationship between energy consumption and economic growth, resources must be found and developed to meet the growing demand for energy through efficient and secure means. Wind, solar, geothermal, and nuclear energy are alternative energy sources contributing significantly less or no greenhouse gases.

Nuclear energy is one of the viable alternatives, as it is a carbon-free energy source. However, academics and policymakers have reservations about implementing this type of energy on a big scale. These concerns range from safety concerns at nuclear energy processing plants to proliferation concerns and radioactive waste disposal and its associated expenses. While these worries are legitimate, the benefits of nuclear energy may exceed the drawbacks, particularly for a densely populated developing country such as India with rising energy demand.

This study aims to determine the effect of nuclear energy consumption on CO_2 emissions in India, test the ECK hypothesis for the country, and examine the GHG-nuclear energy nexus. Fig. 1 presents a pictorial explanation of the ECK hypothesis where environmental decay is seen at lower income levels, and at the peak of economic development, environmental decay begin to decline.

This study makes three key contributions which points out the significance research novelty. To begin, to our knowledge, very few researchers have examined the influence of nuclear energy on air pollution in India recently [2,6,7]. However, their periods are typically shorter. Also, different variables and different models are employed in these studies. Specifically [2,6,7], considered data with

* Corresponding author. Ankara Yıldırım Beyazıt University, Esenboğa Campus, Faculty of Political Sciences, Department of Economics, 06670 Çubuk/Ankara, Turkey.
E-mail addresses: oozgur@ybu.edu.tr (O. Ozgur), veliyilanci@gmail.com (V. Yilanci), maxwellkongkuah@gmail.com (M. Kongkuah).

https://doi.org/10.1016/j.net.2021.11.001

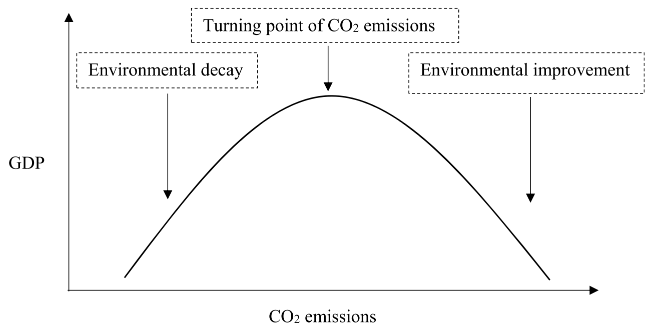

Fig. 1. Environmental Kuznets curve conceptualised.

the end date of either 2013 or 2014 and shorter periods as low as 23 years while the current study uses more recent and 47 years' worth of data. Also, different variables such as coal consumption, oil equivalent, trade openness and population amongst others are used in the studies by Refs. [2,6,7]. While [6] studied sectoral emissions at sub-regional levels in India from 1990 to 2013, the current study is examined at the national level using more recent data. Additionally, nuclear energy provides a novel technique to employ technology as a proxy in the IPAT paradigm. It is classified as a high-tech investment because it is manufactured using advanced technical methods [8]. Again, by generating low-carbon electricity, nuclear energy has gained global recognition as one of the most effective methods for pollution reduction [9], and nuclear energy consumption offers a viable option for greenhouse gas and carbon emission reduction [10]. For example, nuclear energy offset almost 564 million metric tons of CO_2 emissions in 2015, the equivalent of nearly 128 million metric tons of CO_2 released by the transportation sector. On the other side, nuclear energy reduces the costs and budget deficit of fossil fuel-importing countries while also reducing energy dependence and security concerns. Nuclear energy is a non-polluting form of energy necessary for achieving sustainable development goals [11,12]. Nuclear energy is a reliable and safe energy source that promotes economic progress by resolving energy supply issues. This study is the most recent to investigate the phenomena and use the most recent data available. As mentioned in the ensuing text, India warrants special research attention due to its enormous and rising population, which places severe strain on the environment. Most Indians live in rural regions and rely heavily on fossil fuels for cooking and heating, contributing to rising air pollution. India was the third-largest CO_2 emitter in 2018, behind China and the United States. On the other hand, India has a substantial nuclear energy potential, as evidenced by its twenty-two operational nuclear reactors. Thus, if India develops an appropriate and prudent nuclear energy policy, the country's air pollution problem will almost certainly be resolved in the coming years.

Second, in addition to the nuclear energy-environmental pollution connection, this analysis tests the classic Environmental Kuznets Curve (EKC) hypothesis for India, which assumes an inverted U-shaped link between pollution and income.

Third, in contrast to previous research, this work employs a newly modified Autoregressive Distributive Lag (ARDL) cointegration test based on a Fourier function presented by Ref. [13]. Unlike [2,7] which employed the ARDL and DARDL models, the current study employed the Fourier ARDL (FARDL) which has several desirable qualities. For instance, there is no precondition on the integration levels of the regressors; they could be stationary at the level or the first differences. Additionally, the test enables several seamless structural changes. As previously stated, this study's methods tackle two significant weaknesses in the literature, including the following. To begin, they assume that the total number of structural changes is known. Second, they permit only abrupt structural changes, as dummy variables are used to capture the changes.

The rest of the article is structured in the following manner. Section 2 reviews the literature, Section 3 summarizes the data and methods, Section 4 discusses the empirical findings, and Section 5 closes the study with some policy recommendations.

2. Literature review

There has been much effort to examine the relationship between nuclear energy consumption, economic growth, and environmental pollution, albeit with inconclusive results. The current study discusses the literature in several strands as follows:

The first group of studies evaluates the performance of nuclear energy and renewable energy sources in reducing environmental degradation [14]. provided evidence for the unidirectional causality from nuclear energy consumption to CO_2 emissions. They revelated that nuclear energy is a more practical tool than renewable energy sources in reducing gas emissions in the US. However [15], found that nuclear energy sources perform better than nuclear energy generation in reducing gas emissions in the US. They argued that the functional form of the specified model and the inclusion of energy prices matter in comparing the performance of alternative sources [16]. studied the effectiveness of nuclear energy and renewable energy consumption in reducing gas emissions in the United States by controlling income and energy consumption. In his research, he discovered that nuclear energy consumption reduces greenhouse gas emissions in the short and long run, whereas renewable energy consumption is only effective in the short run.

Similarly [11,17], and [12] found that renewable energy consumption plays a more critical role than nuclear energy consumption to reduce environmental degradation in nine developed countries, China and South Africa respectively [10]. have demonstrated in a study of 30 countries that increasing the use of nuclear energy is not environmentally advantageous than using renewable energy sources.

However, the long-term review of [18] showed that nuclear power plays a more robust role than the effect of renewable energy use in reducing air pollution in 18 countries. More recently [4], demonstrated that both nuclear energy generation and renewable energy consumption reduces air pollution in BRICS countries. Similarly [5], illustrated the significant role of nuclear energy and renewable energy in reducing carbon emissions in many of the selected OECD countries. Correspondingly, this study has provided policymakers a combination of nuclear and renewable energy sources to minimize deterioration of the environment.

[19] provided evidence favoring nuclear energy and renewable energy's role in mitigating the CO2 emissions in most of the Comprehensive and Progressive Agreement for Trans-Pacific Partnership (CPTPP) countries and demonstrated that trade openness facilitates the reduction in gas emissions. Similarly, the findings of [20] for ten highest CO2 emitting counties favor the significant role of nuclear and renewable energy generation to promote a clean environment. For Spain [21], considered nonlinearities in the current relationship and revealed that the use of nuclear power mitigates the CO2 emissions in the expansion period. Therefore, they concluded that nuclear energy contributes to the clean air.

On the one hand [22], found that CO_2 emissions, economic growth, and nuclear energy consumption are cointegrated in the long run. Nevertheless, their findings have shown that nuclear energy positively affects gas emissions in developed and developing countries. They also found that conservative policies effectively reduce gas emissions without damaging economic growth in developing countries [1]. also provide evidence supporting the significant positive impact of nuclear energy consumption on air pollution in Pakistan both in the short and the long run.

On the other hand [23], provided supporting evidence for nuclear energy consumption in boosting economic growth and preventing air pollution in 30 major nuclear consumer countries [24]. presented a significant impact of nuclear generation efforts to reduce air pollution for a sample of 12 nuclear generator countries. They also found that CO_2 emissions decrease monotonically with economic growth that contradicts the EKC hypothesis [25]. investigate the existence of a long-run relationship among income, nuclear energy and CO2 in Canada, France, Japan, Korea, Spain, and the USA by using Johansen cointegration test. Having found a long-run relationship, the study concluded that nuclear energy has a decreasing effect on CO2. Besides, the findings of the study indicate mixed results for income - Co2 emissions relationship. Similarly [26], analyzed the relationship among energy consumption, nuclear energy, CO2 emissions and income in 12 nuclear generating countries by employing first-generational panel data techniques. The results provide evidence that while nuclear energy and economic growth have a decreasing effect on Co2 emissions, energy consumption has a detrimental effect [3]. constructed a dynamic panel data model and provided supporting evidence favoring nuclear energy's role in reducing environmental degradation without harming economic growth in 18 OECD countries.

The second group of studies focuses on the relationship between nuclear energy consumption and economic growth using causality and cointegration techniques. In this context [27], provided evidence favoring the bidirectional causal relationship between nuclear energy consumption and economic growth in a sample of 16 countries [28]. examined the causal relationship between nuclear energy consumption and economic growth in the US. However, their findings indicated no causal linkage between nuclear energy and economic activity and favored the neutrality hypothesis [29]. also found supporting evidence for the neutrality hypothesis in most OECD countries.

For France [30], examined the impact of nuclear energy on CO_2 emissions by controlling trade and urbanization. They provided evidence favoring the EKC hypothesis and found that nuclear energy consumption significantly reduces gas emissions. However [31], found that nuclear energy consumption is an effective tool in mitigating the gas emissions in Finland, Japan, Korea, and Spain among 11 OECD countries.

Conversely [32], argued that the consumption of nuclear energy causes economic growth. Conservative policies to reduce nuclear energy could impede Spain, the United Kingdom, and the USA [33]. also provided evidence for the significant role of nuclear energy consumption to boost economic growth in Taiwan [34]. showed that nuclear energy consumption enhances economic activity in three Latin American countries [35]. also illustrated that the energy conservation policies would reduce economic activity in four developing countries. However [9], found no causal relationship between nuclear energy consumption and economic activity in 18 developed and developing countries.

Studies on nuclear energy consumption in India focus mainly on nuclear energy consumption on economic activities. The literature neglects the nexus of nuclear-energy generation-environmental degradation. Of these studies of India [36], found that reducing nuclear energy consumption hampers economic activity [37]. also suggested increasing nuclear energy investments in India since nuclear energy generation fosters economic growth.

[38] developed a dynamic panel data model that examined the effects of various factors on nuclear energy consumption in 17 developed and developing countries. They found that higher CO_2 emissions raise the demand for nuclear energy in India [7]. handled an ARDL model and found that nuclear energy consumption performs better to reduce India's air pollution. Their findings provided evidence for policymakers to alternate fossil fuel consumption to nuclear energy sources [39]. found that nuclear energy generation policies have transitory effects in India. More recently [40], provided evidence for the beneficial role of nuclear energy generation for sustainable economic development and favored the government's encouraging electricity generation through the nuclear source.

The related literature demonstrates that the role of nuclear energy generation in mitigating CO_2 emissions is albeit with mixed results in various countries. Therefore, one might conclude that there is room to contribute to the ongoing debate by utilizing recent methodological techniques.

3. Data and methodology

3.1. Data

Intending to test the effect of nuclear energy consumption on environmental degradation in India, we employ annual data covering the period from 1970 to 2016. For the indicator of environmental degradation, we employ per capita carbon emissions (CO_2) that is measured in metric tons, besides, we use per capita gross domestic product (constant 2010 US$) (GDP hereafter) and per capita nuclear energy consumption (NE) measured in tons of oil equivalent. We obtained CO_2 and GDP from the open data system of the World Bank,[1] NE from BP statistical review.[2]

3.2. Fourier ARDL bootstrap cointegration test

Traditional cointegration tests induce non-rejection of the null of no-cointegration in the case of structural breaks in the cointegration relationship, as shown by Ref. [41]. Therefore, several cointegration tests with structural breaks have been introduced to the literature (see Refs. [41–44]. However, most of these studies have mainly two shortcomings. First, they have the assumption that the number of structural changes is known. Second, they only allow sudden structural changes since they employ dummy variables to capture the changes.

Nevertheless [45] stated that “most things change slowly over time.” So, in this paper, we use the modified Autoregressive Distributive Lag (ARDL) cointegration test with a Fourier function proposed by Ref. [13]. The Fourier ARDL (FARDL) has some attractive properties. There is no pre-condition about the regressors' integration levels; they could be stationary at level or stationary at the first differences. Besides, the test allows multiple smooth structural changes.

To investigate the influence of nuclear energy and gross domestic product on carbon emissions, by following the studies of [1], we use the following model:

$$\ln(CO_2)_t = \beta_1 + \beta_2 \ln GDP_t + \beta_3 \ln GDP_t^2 + \beta_4 \ln NE_t + u_t \quad (1)$$

CO_2 indicates carbon dioxide emissions, GDP, GDP^2 and NE stands for gross domestic product, GDP square, and nuclear energy, respectively. In this equation β_1 is the constant term, while u_t shows the error term. We use CO_2 as an indicator for environmental degradation which is known as the most important, in terms of impact on climate change and human-caused greenhouse gases. To

[1] World Bank, (2020). https://data.worldbank.org/.

[2] BP, bp Statistical Review of World Energy June 2020, http://www.bp.com/statisticalreview.

see the effect of nuclear energy consumption on the CO_2, we include the NE to the equation and control for income adding. To test the EKC hypothesis, square of GDP incorporated to the equation. If slope coefficients of GDP and GDP^2 are found as statistically significant, and $\beta_1 > 0$ $\beta_2 < 0$, then one can conclude that the EKC hypothesis is confirmed. The coefficient of NE is expected as negative.

We can re-express Eq. (1) in an unrestricted error correction representation, as follows:

$$\Delta \ln CO_t^2 = d(t) + \alpha_2 \ln CO_{t-1}^2 + \alpha_3 \ln GDP_{t-1} + \alpha_4 \ln GDP_{t-1}^2 + \alpha_5 \ln NE_{t-1} + \sum_{i=1}^{p_1} \theta_i' \Delta \ln CO_{t-i}^2 + \sum_{i=0}^{p_2} \phi_i' \Delta \ln GDP_{t-i} + \sum_{i=0}^{p_3} \phi_i' \Delta \ln GDP_{t-i}^2 + \sum_{i=0}^{p_4} \gamma_1' \Delta \ln NE_{t-i} + e_t \quad (2)$$

where Δ and p are the first difference operator and optimal lag length respectively. $d(t)$ indicates a deterministic term as

$$d(t) = \alpha_1 + \lambda_1 \sin\left(\frac{2\pi kt}{T}\right) + \lambda_2 \cos\left(\frac{2\pi kt}{T}\right) \quad (3)$$

where $\pi = 3.1416$, k is a particular frequency that is used for approximating an unknown number of structural changes that occur in unknown locations, and t and T show the trend term and sample size, respectively. The optimal lag length and the optimal value of k that lies in the interval $k = [0.1, \ldots, 5]$, is chosen using Akaike Information Criteria. The reason behind allowing fractional frequencies is they are able to capture permanent breaks while integer frequencies imply temporary breaks.

Following suggestions of [46,47], we can test the null hypothesis of no cointegration relationship by using F-test (F_A), t-test (t), and F-test (F_B), as in Eq. (3).

$$H_{0A} : \beta_1 = \beta_2 = \beta_3 = 0, \ldots\ldots. H_{0t} : \beta_1 = 0, \ldots\ldots.. H_{0B} : \beta_2 = \beta_3 = 0$$

The null hypothesis can be rejected if all of F_A, F_B, and t are significant. Remaining cases shows no-cointegration between the variables. The necessary critical values are obtained via bootstrap simulations, so, there is no possibility of in conclusion about the hypotheses.

4. Empirical results

We begin the analysis by determining the integration levels of the variables for the FARDL cointegration test. There is a condition that the dependent variable must be integrated at the first difference while the regressors could be either level stationary or stationary at the first difference. We implemented two tests; Augmented Dickey-Fuller (ADF) and Fourier ADF unit root tests. The latter is suggested by Ref. [48] and augments the ADF unit root test regression with a Fourier function to allow multiple smooth structural changes. We presented the results of both tests in Table 1.

Before employing the Fourier ADF unit root test, we first test the significance of the Fourier function. If the Fourier function is statistically significant, we can use the Fourier ADF unit root. Otherwise, we should employ the ADF unit root test to evaluate the stationarity properties of the series. Test results in Table 1 show that Fourier functions for GDP and GDP^2 are found as significant. Thus, we test the null using the Fourier ADF unit root test for these variables, which shows that both variables are stationary. Next, we conducted the remaining two variables to the ADF unit root test and obtained that both variables are integrated at the first differences. Since the unit root characteristics of the variables provide the precondition, we can employ the FARDL cointegration test to examine the long-run relationship between the variables by using the model specification in Eq. (1). Table 2 presents the test results:

Table 1
Unit root test results.

Variables	Fourier ADF Unit Root Test		ADF Unit Root Test	
	Level		Level	First Differences
	F test	Test Statistics		
Co2	5.919		0.833 (0.994) [0]	−6.548 (0) [0]*
GDP	15.727*	−4.952 {0.1} [1]	4.063 (1) [0]	−5.670 (0) [0]*
GDP²	14.953*	−4.863 {0.1} [1]	4.996 (1) [0]	−5.011 (0) [0]*
NE	5.178		−0.898 (0.780) [0]	−8.993 (0) [0]*

Note: * shows the significance at the 1% level. Numbers in parenthesis, bracelets, and brace indicate p-values, optimal lag-length chosen as using Akaike information criteria, and optimal frequency chosen using the sum of squared residuals. 1% critical values for the F test and Fourier ADF test are 12.21 and 4.491, respectively [Obtained from Enders and Lee, 2012; Bozoklu et al., 2020].

Since all the test statistics are higher than the critical values at the traditional significance levels, we conclude that there is a cointegration relationship between the variables. Before proceeding to estimate short-run and long-run coefficients, we applied diagnostic tests for our empirical model.[3] Diagnostic test results indicate that the ARDL model is free of serial autocorrelation and heteroscedasticity. Besides, the model has reasonably high goodness of fit measures, and the CUSUM graphs show the stability of the model.

In the next step, we estimate long and short-run coefficients and present the results in Table 3.

Empirical results in Table 3 show that all the coefficients are statistically significant. The coefficient of lnGDP is positive and implies that economic growth increases air pollution. However, the coefficient of $\ln GDP^2$ is negative in the long run. This means that the coefficients of income variables alternate in sign and provide evidence favoring the EKC for India. Therefore, the relationship between income level and CO_2 emissions exhibits a U-shaped relationship. Thus, it seems that all relevant implications of the EKC hypothesis work for the Indian economy. One might conclude that the rise in income level has a different impact on air pollution measures in India's various stages of economic development. Although the increase in income level causes environmental degradation up to a certain degree, the ongoing rise after the threshold level improves the environmental quality.

Besides, it seems that nuclear energy consumption contributes to reducing air pollution since the coefficient of NE is significantly negative. More formally, the results indicate that a 1% increase in nuclear energy consumption decreases CO_2 by 0.148% in the long run. The nuclear energy conservative policies would increase air pollution and deteriorates the environmental quality in India. Nuclear energy generation would be an alternative and clean way of energy consumption to provide sustainable economic growth. Therefore, these results urge policymakers to promote nuclear energy generation investments to protect the environment. Empirical findings of our study support the view of increasing nuclear energy generation to reduce the harmful effects of greenhouse gas releases in driving global warming and climate change [40]. Since nuclear energy generation would also be an efficient way of providing energy security for energy-dependent countries, encouraging nuclear energy consumption would offer sustainable

[3] Diagnostics tests for the ARDL model is presented in the Appendix.

Table 2
Fourier ARDL cointegration test results.

Selected Model		Optimal Frequency	AIC	
FARDL (1, 0, 2, 4)		1.56	−4.692	
Test Statistics		Bootstrap Critical Values		
		0.90	0.95	0.99
F_A	4.123***	3.674	4.519	6.655
T	−3.939**	−2.889	−3.361	−4.264
F_B	5.424*	2.972	3.719	5.421

*, **, and *** indicate significance at 1%, 5%, and 10% levels, respectively. We performed 5000 simulations to obtain the critical values.

Table 3
Long-run estimation results.

Panel (a)	Long-term coefficient based on FARDL procedure	
Variables	Coefficients	p-value
lnGDP	5.422	0.000
$lnGDP^2$	−0.312	0.000
lnNE	−0.148	0.000
Constant	−23.164	0.000

Note: *, ** and *** show the significance at 1%, 5% and 10% levels, respectively.

economic growth [4].

These findings are consistent with [7,40]. However, our findings are partially consistent with [23], which provides the negative but insignificant impact of nuclear energy use in environmental pollution for India.

The short-run impact of the income and nuclear energy consumption on CO_2 emissions are presented in Table 4.

In the short-run Vector Error Correction Model (VECM), since the lagged ECT is statistically significant and has a value of 0 and -1, one can state that the error correction mechanism is working. The coefficient of the term ECT (−0.811) implies that approximately 81% of the deviations from CO2 emissions will be corrected within a year and that it will take less than a half year to return to equilibrium.

Table 4 shows that current and lagged values of $lnGDP^2$ and lnNE are significant on the carbon emissions in the short run. These findings demonstrate that the current value of NE reduces CO_2 and implies that nuclear energy use in the current period contributes to reducing carbon emissions. However, the lagged values of nuclear energy consumption significantly positively impact CO_2 emissions in the short run. This result shows that the increases in the previous periods in nuclear energy consumption pollute the environment.

By comparing the impact of nuclear energy use on short- and long-term CO2 emissions, it appears that nuclear energy use has a more significant effect on long-term air pollution mitigation. This means the country is taking advantage of nuclear power overtime

Table 4
Short-run estimation results.

	Short-term coefficient based on FARDL procedure	
Variables	Coefficients	p-value
$D(lnGDP^2)$	−0.308*	0.000
$D(lnGDP^2(-1))$	−0.044*	0.001
D(lnNE)	−0.053*	0.004
D(lnNE(-1))	0.053*	0.002
D(lnNE(-2))	0.038**	0.026
D(lnNE(-3))	0.039**	0.021
ECT_{t-1}	−0.811*	0.000

Note: *, ** and *** show the significance at 1%, 5% and 10% levels, respectively.

to mitigate greenhouse gas emissions. The environmental role of short-term nuclear energy consumption is in line with [7].

Both long-run and short-run estimation results for India demonstrate that nuclear energy generation is a practical tool to mitigate environmental degradation and reduce the harmful effects of energy consumption on climate change and sustainable development. However, the establishment of nuclear energy power plants and the generation of energy through radioactive sources create some risks [40]. Therefore, new investments and the establishment of nuclear power plants should be conducted carefully and safely [27].

5. Conclusion

The rise in industrialization and globalization throughout the world increased the energy demand in the recent era. The increase in the use of fossil fuels produced immense adverse effects on the environment. The burning of fossil fuels increased the level of greenhouse gas emissions and generated environmental stress. The rise of environmental degradation increased the awareness of nature, and countries started to use clean energy sources to meet their energy demand.

Nuclear energy, therefore, is used to struggle with greenhouse gas emissions as a clean energy source. Although there are safety concerns about establishing large-scale nuclear power generators, many developed and developing countries increased their electricity generation through nuclear elements.

The primary aim of this study is to investigate the impact of nuclear energy consumption on CO_2 emissions in India over the period between 1970 and 2016. In such an analysis, India provides an ideal laboratory environment since it is one of the fast-growing economies with a huge need for energy and higher gas emissions. Unlike many studies in the literature, our study handles FARDL methodology in which inserted Fourier terms to catch the structural changes as smooth and gradual processes.

The primary finding of the Fourier ARDL bounds test indicated that nuclear energy consumption is cointegrated with CO_2 emissions and GDP. The long-run coefficient estimation results of the FARDL procedure demonstrate that the coefficient of GDP alternates in sign. The significantly positive coefficient of the lnGDP variable and significantly negative coefficient of $lnGDP^2$ provide evidence favoring the EKC hypothesis in India. Another relevant finding of the long-run estimation result is that the negative coefficient of the NE consumption is statistically significant. Therefore, our findings provide evidence favoring the role of nuclear energy as an alternative clean energy source to sustain economic growth and enable a sustainable environment in India in the log-run.

Our long-run empirical results favor nuclear energy as a source of clean energy. Similar to renewable sources, nuclear power plants seem to generate electricity in a more environment-friendly way. As a result, while nuclear power plants require more investments, they serve to reduce environmental degradation and promote economic activity in a cleaner manner as is not the case for fossil fuels.

The short-run VECM results also support nuclear energy's critical role as a clean energy source and an effective alternative to fossil fuels in mitigating environmental degradation. Also, the short-run estimation results suppose that the higher share of environmental disorders is corrected within a year. Therefore, this finding illustrates that the environmental policies are effective.

These findings might generate potential implications for policymakers. First, expanding the capacity of nuclear power plants is critical for achieving sustainable and clean growth. The Indian government and policymakers must generate a large portion of the energy they require from nuclear power. Nuclear energy is significantly cleaner than other energy sources such as fossil fuels. Second, policymakers can benefit from enacting new ecological policies and nuclear energy investments to strangle greenhouse gas emissions and resolving environmental degradation problems. It also provides an incentive for policymakers, since nuclear energy reduces reliance on imported oil and petroleum products, improves the existing balance sheet, it might be an effective tool to boost economic growth in the long run. The use of nuclear energy in electricity generation will also help to provide an energy security for India. As a result, India is less affected by future global instabilities in energy production and trade. On the other hand, policymakers also should be aware of the potential dangers and the security issues of nuclear power generation. Therefore, policymakers need to take security measures in nuclear power plants to prevent disasters.

Since our study focuses on the linear analysis of the nuclear energy and gas emissions nexus there are still some limitations. Therefore, further research could address the nonlinearities of the role of nuclear energy generation in mitigating environmental degradation.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2021.11.001.

References

[1] N. Mahmood, Z. Wang, B. Zhang, The role of nuclear energy in the correction of environmental pollution: evidence from Pakistan, Nuclear Engineering and Technology 52 (6) (2020) 1327–1333, https://doi.org/10.1016/j.net.2019.11.027.
[2] Danish, B. Ozcan, R. Ulucak, An empirical investigation of nuclear energy consumption and carbon dioxide (CO2) emission in India: bridging IPAT and EKC hypotheses, Nuclear Engineering and Technology 53 (6) (2021) 2056–2065, https://doi.org/10.1016/j.net.2020.12.008.
[3] L.S. Lau, C.K. Choong, C.F. Ng, F.M. Liew, S.L. Ching, Is nuclear energy clean? Revisit of Environmental Kuznets Curve hypothesis in OECD countries, Econ. Modell. 77 (2019) 12–20, https://doi.org/10.1016/j.econmod.2018.09.015.
[4] S.T. Hassan, M.A. Baloch, Z.H. Tarar, Is nuclear energy a better alternative for mitigating CO2 emissions in BRICS countries? An empirical analysis, Nuclear Engineering and Technology 52 (12) (2020) 2969–2974, https://doi.org/10.1016/j.net.2020.05.016.
[5] K. Saidi, A. Omri, Reducing CO2 emissions in OECD countries: do renewable and nuclear energy matter? Prog. Nucl. Energy 126 (2020), 103425 https://doi.org/10.1016/j.pnucene.2020.103425.
[6] A. Garg, et al., CO2 emission in India: trends and management at sectoral, subregional and plant levels, Carbon Manag. 8 (2) (2017) 111–123, https://doi.org/10.1080/17583004.2017.1306406.
[7] R. Rani, N. Kumar, Does nuclear energy consumption improve environment? Empirical evidence from India, Nat. Environ. Pollut. Technol. 16 (4) (2017) 1075–1079.
[8] B. Muhammad, Energy consumption, CO2 emissions and economic growth in developed, emerging and Middle East and North Africa countries, Energy (2019) 232–245, https://doi.org/10.1016/j.energy.2019.03.126.
[9] M. Ben Mbarek, K. Saidi, M. Amamri, The relationship between pollutant emissions, renewable energy, nuclear energy and GDP: empirical evidence from 18 developed and developing countries, Int. J. Sustain. Energy 37 (6) (2018) 597–615, https://doi.org/10.1080/14786451.2017.1332060.
[10] T. Jin, J. Kim, What is better for mitigating carbon emissions—Renewable energy or nuclear energy? A panel data analysis, Renew. Sustain. Energy Rev. 91 (2018) 464–471, https://doi.org/10.1016/j.rser.2018.04.022.
[11] K. Dong, R. Sun, H. Jiang, X. Zeng, CO2 emissions, economic growth, and the environmental Kuznets curve in China: what roles can nuclear energy and renewable energy play? J. Clean. Prod. 196 (2018) 51–63.
[12] S.A. Sarkodie, S. Adams, Renewable energy, nuclear energy, and environmental pollution: accounting for political institutional quality in South Africa, Sci. Total Environ. 643 (2018) 1590–1601, https://doi.org/10.1016/j.scitotenv.2018.06.320.
[13] V. Yilanci, S. Bozoklu, M.S. Gorus, Are BRICS countries pollution havens? Evidence from a bootstrap ARDL bounds testing approach with a Fourier function, Sustainable Cities and Society 55 (2020), 102035.
[14] K. Menyah, Y. Wolde-Rufael, CO2 emissions, nuclear energy, renewable energy and economic growth in the US, Energy Pol. 38 (6) (2010) 2911–2915.
[15] M. Jaforullah, A. King, Does the use of renewable energy sources mitigate CO2 emissions? A reassessment of the US evidence, Energy Econ. 49 (2015) 711–717.
[16] J. Baek, Do nuclear and renewable energy improve the environment? Empirical evidence from the United States, Ecol. Indicat. 66 (2016) 352–356.
[17] K. Saidi, M.B. Mbarek, Nuclear energy, renewable energy, CO2 emissions, and economic growth for nine developed countries: evidence from panel Granger causality tests, Prog. Nucl. Energy 88 (2016) 364–374.
[18] S. Lee, M. Kim, J. Lee, Analyzing the impact of nuclear power on CO2 emissions, Sustainability 9 (8) (2017) 1428.
[19] D.H. Vo, A.T. Vo, C.M. Ho, H.M. Nguyen, The role of renewable energy, alternative and nuclear energy in mitigating carbon emissions in the CPTPP countries, Renew. Energy 161 (2020) 278–292, https://doi.org/10.1016/j.renene.2020.07.093.
[20] A. Azam, M. Rafiq, M. Shafique, H. Zhang, J. Yuan, Analyzing the effect of natural gas, nuclear energy and renewable energy on GDP and carbon emissions: a multi-variate panel data analysis, Energy 219 (2021), 119592, https://doi.org/10.1016/j.energy.2020.119592.
[21] M. Piłatowska, A. Geise, A. Włodarczyk, The effect of renewable and nuclear energy consumption on decoupling economic growth from CO2 emissions in Spain, Energies 13 (9) (2020) 2124, https://doi.org/10.3390/en13092124.
[22] A. Alam, Nuclear energy, CO2 emissions and economic growth: the case of developing and developed countries, J. Econ. Stud. 40 (6) (2013) 822–834.
[23] U. Al-Mulali, Investigating the impact of nuclear energy consumption on GDP growth and CO2 emission: a panel data analysis, Prog. Nucl. Energy 73 (2014) 172–178.
[24] J. Baek, A panel cointegration analysis of CO2 emissions, nuclear energy and income in major nuclear generating countries, Appl. Energy 145 (2015) 133–138.
[25] J. Baek, D. Pride, On the income-nuclear energy-CO2 emissions nexus revisited, Energy Econ. 43 (2014) 6–10, https://doi.org/10.1016/j.eneco.2014.01.015.
[26] J. Baek, A panel cointegration analysis of CO2 emissions, nuclear energy and income in major nuclear generating countries, Appl. Energy 145 (2015) 133–138, https://doi.org/10.1016/j.apenergy.2015.01.074.
[27] N. Apergis, J.E. Payne, A panel study of nuclear energy consumption and economic growth, Energy Econ. 32 (3) (2010) 545–549.
[28] J.E. Payne, J.P. Taylor, Nuclear energy consumption and economic growth in the US: an empirical note, Energy Sources B Energy Econ. Plann. 5 (3) (2010) 301–307.
[29] S. Nazlioglu, F. Lebe, S. Kayhan, Nuclear energy consumption and economic growth in OECD countries: cross-sectionally dependent heterogeneous panel causality analysis, Energy Pol. 39 (10) (2011) 6615–6621.
[30] H. Iwata, K. Okada, S. Samreth, Empirical study on the environmental Kuznets curve for CO2 in France: the role of nuclear energy, Energy Pol. 38 (8) (2010) 4057–4063.
[31] H. Iwata, K. Okada, S. Samreth, Empirical study on the determinants of CO2 emissions: evidence from OECD countries, Appl. Econ. 44 (27) (2012) 3513–3519.
[32] Y. Wolde-Rufael, K. Menyah, Nuclear energy consumption and economic growth in nine developed countries, Energy Econ. 32 (3) (2010) 550–556.
[33] H.P. Lin, L.T. Yeh, H.C. Tsui, S.C. Chien, Nuclear and non-nuclear energy consumption and economic growth in Taiwan, Energy Sources B Energy Econ. Plann. 10 (1) (2015) 59–66.
[34] I. Ozturk, Measuring the impact of alternative and nuclear energy consumption, carbon dioxide emissions and oil rents on specific growth factors in the panel of Latin American countries, Prog. Nucl. Energy 100 (2017) 71–81.
[35] H. Naser, Analysing the long-run relationship among oil market, nuclear energy consumption, and economic growth: an evidence from emerging economies, Energy 89 (2015) 421–434.
[36] Y. Wolde-Rufael, Bounds test approach to cointegration and causality between nuclear energy consumption and economic growth in India, Energy Pol.

38 (1) (2010) 52−58.
[37] J.Y. Heo, S.H. Yoo, S.J. Kwak, The causal relationship between nuclear energy consumption and economic growth in India, Energy Sources B Energy Econ. Plann. 6 (2) (2011) 111−117.
[38] A. Omri, N.B. Mabrouk, Sassi-Tmar, A, Modeling the causal linkages between nuclear energy, renewable energy and economic growth in developed and developing countries, Renew. Sustain. Energy Rev. 42 (2015) 1012−1022.
[39] G. Gozgor, E. Demir, Evaluating the efficiency of nuclear energy policies: an empirical examination for 26 countries, Environ. Sci. Pollut. Control Ser. 24 (22) (2017) 18596−18604.
[40] R. Ulucak, Ozcan B. Danish, An empirical investigation of nuclear energy consumption and carbon dioxide (CO2) emission in India: bridging IPAT and EKC hypotheses, Nucl. Eng. Technol. (2020), 104743, https://doi.org/10.1016/j.net.2020.12.008.
[41] Allan W. Gregory, B.E. Hansen, Residual-based tests for cointegration in models with regime shifts, J. Econom. 70 (1) (1996) 99−126.
[42] S. Johansen, R. Mosconi, B. Nielsen, Cointegration analysis in the presence of structural breaks in the deterministic trend, Econom. J. 3 (2) (2000) 216−249.
[43] A. Hatemi-j, Tests for cointegration with two unknown regime shifts with an application to financial market integration, Empir. Econ. 35 (3) (2008) 497−505.
[44] D. Maki, Tests for cointegration allowing for an unknown number of breaks, Econ. Modell. 29 (5) (2012) 2011−2015.
[45] R.J. Hyndman, Measuring Forecast Accuracy, Business Forecasting: Practical Problems and Solutions, 2014, pp. 177−183.
[46] M.H. Pesaran, Y. Shin, R.J. Smith, Bounds testing approaches to the analysis of level relationships, J. Appl. Econom. 16 (3) (2001) 289−326.
[47] R. McNown, C.Y. Sam, S.K. Goh, Bootstrapping the autoregressive distributed lag test for cointegration, Appl. Econ. 50 (13) (2018) 1509−1521.
[48] W. Enders, J. Lee, The flexible Fourier form and Dickey−Fuller type unit root tests, Econ. Lett. 117 (1) (2012) 196−199.