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Nexus between Nuclear Energy, Economic Growth, and Greenhouse Gas Emissions in India

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ABSTRACT

The escalating demand for fossil fuels in India has resulted in a significant strain on the environment due to the amplified emissions of greenhouse gases (GHGs). Nevertheless, India possesses a significant capacity for nuclear energy, as seen by its 22 operational nuclear reactors. This capacity holds promise for reducing GHG emissions. This research utilized a dataset spanning from 1969 to 2021 to examine the impact of nuclear energy utilization on GHG emissions. The study also aimed to verify the validity of the environmental Kuznets curve (EKC) hypothesis in India, employing the Autoregressive Distributive Lag (ARDL) model. The findings suggest that the EKC is applicable to India. Furthermore, it has been observed that a marginal increase of 1% in the use of nuclear energy leads to a reduction of GHG by 0.02% in the immediate term and 0.16% in the long term. This finding highlights the significance of expanding nuclear power as a crucial policy objective in order to attain environmentally friendly and sustainable economic development.

Keywords: Nuclear Energy, GHG Emissions, Economic Growth, Emission Reduction, Sustainable Development
JEL Classifications: R10, P18, O40, Q20,Q40

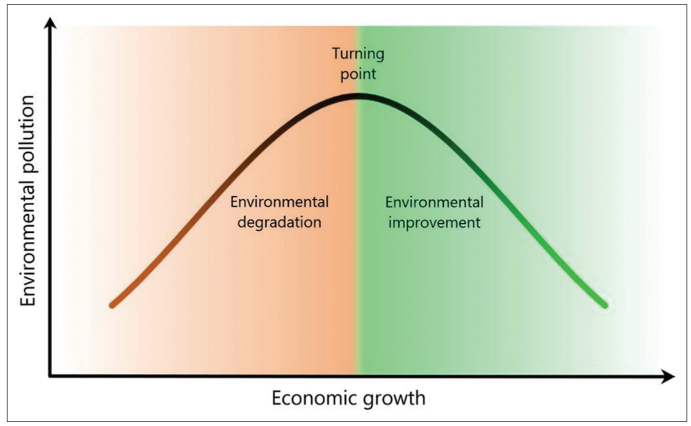
1. INTRODUCTION

The utilization of energy has shown exponential growth in the contemporary period compared to previous historical periods (Voumik et al., 2022; Akter et al., 2023). The generation of energy derived from fossil fuels is known to contribute to the phenomenon of global warming and climate change by releasing significant amounts of GHGs (Raihan, 2023a; Voumik et al., 2023a; Zimon et al., 2023; Zimon and Zimon, 2020). Over the past few years, there has been a substantial rise in GHG emissions, and it is anticipated that this upward trend will persist in the foreseeable future (Raihan, 2023b; Sultana et al., 2023a). A prolonged and continuing discourse has ensued over the amelioration of global warming and the reduction of emissions (Begum et al., 2020; Sultana et al., 2023b; Salehi et al., 2022). Considering the inevitable expansion of global energy consumption and its correlation with economic growth, it becomes imperative to identify and use resources that can effectively and reliably cater to the increasing energy demand in a sustainable and secure manner (Raihan and Tuspekova, 2022a). Alternative energy sources such as wind, solar, geothermal, and nuclear power play a substantial role in mitigating GHG emissions, either by dramatically reducing their output or by not emitting them altogether (Abadie & Gardeazabal 2003; Ghosh et al., 2023; Raihan et al., 2023; Voumik et al., 2023b).

Nuclear energy is a promising alternative due to its carbon-neutral characteristics (Sadiq et al., 2023). Furthermore, nuclear energy offers a unique approach to utilize technology as a surrogate in the IPAT (impact of population, affluence and technology) framework. The categorization of this product as a high-tech investment stem from its production process, which utilizes sophisticated technical methodologies. Once again, the generation of low-carbon power has positioned nuclear energy as a globally recognized and highly efficient approach to mitigating pollution (Zeraibi et al., 2023). Consequently, the utilization of nuclear energy presents a feasible avenue for reducing GHG emissions (Kartal et al., 2023). As an illustration, on an annual basis, the utilization of nuclear-generated power serves to mitigate over 470 million metric tons of GHG emissions that would otherwise be emitted by the combustion of fossil fuels. This is equivalent to removing almost 100 million passenger vehicles from the road. In contrast, nuclear energy offers the potential to mitigate the financial burden and budgetary deficits faced by nations reliant on fossil fuel imports, concurrently addressing concerns surrounding energy reliance and security (Omri and Saadaoui, 2023; Baek 2016). Nuclear energy is an environmentally friendly source of energy that plays a crucial role in the attainment of sustainable development objectives (Adebayo et al., 2023; Pattak et al., 2023). Nuclear energy is widely regarded as a dependable and secure energy source that contributes to economic advancement by effectively addressing challenges related to energy supply (Jahanger et al., 2023).

Nevertheless, there are concerns among scholars and policymakers regarding the widespread adoption of nuclear energy. The concerns encompass a wide range of issues, including safety concerns pertaining to nuclear energy processing plants, worries related to proliferation, and the challenges connected with radioactive waste disposal and its accompanying costs (Yang et al., 2023). Although valid concerns exist, the advantages of nuclear energy may outweigh the disadvantages, especially for a densely populated developing nation like India that is experiencing a growing need for energy. India merits significant research focus owing to its substantial and escalating population, which imposes considerable stress on the environment. A significant proportion of the Indian population resides in rural areas and is heavily dependent on fossil fuels for their cooking and heating needs, hence exacerbating the issue of escalating air pollution. India ranks as the third highest emitter of GHGs, following China and the United States (Raihan and Tuspekova, 2022b). In contrast, India possesses a considerable capacity for nuclear energy, as demonstrated by the presence of 22 functional nuclear reactors inside its borders. Therefore, it can be inferred that the implementation of a well-designed and cautious nuclear energy program in India has the potential to effectively address the prevailing issue of air pollution in the foreseeable future. Nevertheless, a notable study void exists within the current body of literature about the correlation between nuclear energy and GHG emissions, specifically within the Indian context. This research gap hinders the development of suitable policy recommendations aimed at utilizing nuclear energy to effectively accomplish India's emission reduction objectives. Hence, the primary objective of this research is to assess the impact of nuclear energy consumption on GHG emissions in India, utilizing the conceptual framework of the Environmental Kuznets Curve (EKC) hypothesis. Figure 1 depicts a visual representation of the EKC concept, which posits that environmental degradation is observed at lower levels of income, while at the apex of economic development, environmental degradation starts to diminish. The EKC hypothesis posits a non-linear relationship, specifically an inverted U-shaped pattern, between pollution levels and income.

Figure 1: Environmental Kuznets curve hypothesized



The current study offers multiple contributions that underscore the importance of research novelty. Initially, it is worth noting that there has been limited scholarly investigation of the impact of nuclear energy on air pollution in India in recent times (Garg et al., 2017; Rani and Kumar, 2017; Danish et al., 2021). Nevertheless, the data ranges they possess tend to be of shorter duration. Moreover, many variables and diverse models are utilized in these investigations. Prior research has predominantly focused on data sets that concluded in 2014, with other studies examining shorter time frames of 20-30 years. In contrast, the present study encompasses a far broader range of data spanning 53 years. This study represents the latest examination of the relationship between nuclear energy and GHG emissions, utilizing the most up-to-date data accessible up till the year 2021. Furthermore, prior research has predominantly used carbon dioxide (CO_2) emissions as a representative measure of environmental deterioration, neglecting the broader context of GHG emissions. The study conducted by Garg et al. (2017) focused on analyzing sectoral emissions at sub-regional levels in India during the period from 1990 to 2013. In contrast, the present study investigated national-level emissions using more up-to-date data. Moreover, in conjunction with the correlation between nuclear energy and environmental pollution, this study examines the EKC theory in the context of India. Ultimately, the research proposed policy suggestions with the objective of fostering sustainable development. The study made a significant contribution by emphasizing the importance of promoting nuclear energy and financing nuclear energy technology within the economic activities in India. This approach has the potential to contribute to the achievement of Sustainable Development Goal 7 by ensuring access to affordable, reliable, sustainable, and modern energy for all. The study's findings would provide valuable insights for the effective implementation of policies aimed at achieving emission reduction and fostering a low-carbon economy through the financing of nuclear energy utilization.

2. LITERATURE REVIEW

Considerable research has been dedicated to investigating the correlation between the utilization of nuclear energy, the advancement of economies, and the impact on environmental contamination. However, the findings thus far have been inconclusive. The idea of environmental quality was initially introduced by Grossman and Krueger (1991) through their examination of the correlation between GHG emissions and economic growth. These researchers subsequently provide further explanation regarding the significance of economic growth within the framework of the EKC in defining a prosperous ecosystem. Subsequent to the initial investigation, a multitude of scholarly inquiries have been undertaken throughout the course of the past thirty years, with the aim of scrutinizing the soundness of the EKC theory inside various national or regional contexts. According to a study conducted by Yang et al. (2023), the implementation of a hybrid energy system that integrates nuclear and renewable energy sources has the potential to significantly reduce GHG emissions. The primary objective of the energy transition is to transition towards renewable and sustainable energy sources, such as wind, solar, biofuels, hydro, and nuclear, which exhibit minimal or even negative carbon footprints.

In a study conducted by Hassan et al. (2020), it was found that the utilization and production of nuclear energy in BRICS countries had a significant impact in mitigating air pollution. In a similar vein, the authors Saidi and Omri (2020) have demonstrated the substantial impact of nuclear energy in mitigating carbon emissions across several OECD countries. According to the findings of Lee et al. (2017), the utilization of nuclear power demonstrates a greater degree of effectiveness in mitigating air pollution across 18 nations, when compared to the impact of renewable energy sources. Dong et al. (2018) reported a comparable discovery in the context of China, while Sarkodie and Adams (2018) found a similar result in the case of South Africa. In a study conducted by Saidi and Mbarek (2016), it was determined that the consumption of renewable energy had a greater impact on mitigating environmental degradation in nine industrialized nations, compared to the use of nuclear energy. In a study conducted by Jin and Kim (2018), it was shown that the utilization of nuclear energy does not offer more environmental benefits compared to the usage of renewable energy sources. This conclusion was drawn based on an analysis of data from 30 nations. In a similar vein, these studies have offered policymakers a blend of nuclear and renewable energy sources as a means to mitigate environmental degradation.

Furthermore, the study conducted by Vo et al. (2020) presents compelling evidence supporting the significance of nuclear energy and renewable energy sources in effectively addressing the issue of CO_2 emissions within the majority of the CPTPP nations. Additionally, the research demonstrates that trade liberalization plays a crucial role in facilitating the reduction of GHG emissions. In a similar vein, the research conducted by Azam et al. (2021) highlights the substantial contribution of nuclear and renewable energy generation in fostering environmental cleanliness, as evidenced by their findings pertaining to the ten counties with the greatest CO_2 emissions. In their study, Piłatowska et al. (2020) examined the presence of nonlinearities in the present relationship in the context of Spain. Their findings indicate that the utilization of nuclear power has a mitigating effect on CO_2 emissions throughout the expansion era. Consequently, the researchers arrived at the conclusion that nuclear energy makes a significant contribution to the improvement of air quality.

Al-Mulali (2014) presented empirical evidence that highlights the positive impact of nuclear energy consumption on both economic growth and the mitigation of air pollution in a sample of 30 nations that are significant consumers of nuclear energy. In a study conducted by Baek (2015), the author examined the substantial influence of nuclear energy generation initiatives on the mitigation of air pollution within a sample of 12 countries that utilize nuclear power. The researchers also discovered a consistent decline in CO_2 emissions as economic expansion occurs, which presents a contradiction to the EKC concept. Furthermore, Baek and Pride (2014) conducted a study to examine the presence of a long-term association between income, nuclear energy, and CO_2 levels in Canada, France, Japan, Korea, Spain, and the USA. The researchers employed the Johansen cointegration test for their analysis. After establishing a sustained association, the research investigation reached the conclusion that nuclear energy exhibits a diminishing impact on CO_2 emissions. Moreover, the study's findings demonstrate a varied outcome in the correlation between income and CO_2 emissions. In their study, Lau et al. (2019) developed a dynamic panel data model to examine the relationship between nuclear energy and environmental degradation, while also considering its impact on economic growth. The authors presented empirical evidence from their analysis, which supports the notion that nuclear energy can effectively mitigate environmental degradation in 18 OECD nations, without adversely affecting economic growth.

In their work, Jahanger et al. (2023) using moments quantile regression methodology to examine the temporal ramifications of atomic energy on carbon emissions in the leading nations with nuclear energy. The analysis was conducted using data spanning the years 1990 to 2017. Nuclear energy presents itself as a viable and sustainable alternative to conventional fossil fuels due to its capacity to effectively mitigate CO_2 emissions across all quantiles. The findings not only confirm the negative relationship between quadratic economic growth (GDP squared) and CO_2 emissions but also offer robust evidence in favor of the EKC hypothesis. Sadiq et al. (2023) conducted an evaluation of carbon emissions, nuclear energy, globalization, and technical innovation in the top ten nations with the highest nuclear energy consumption between 1990 and 2017. The study also considered economic growth and the utilization of renewable energy sources. The findings indicate that the reduction of CO_2 emissions represents a viable approach through which nuclear power and technical advancements contribute to cost savings while safeguarding the environment.

According to the findings of Menyah and Wolde-Rufael (2010), nuclear energy emerges as a more viable option compared to renewable energy sources for the purpose of mitigating GHG emissions in the United States. Jaforullah and King (2015) conducted a study which revealed that nuclear energy sources have superior performance in terms of decreasing gas emissions compared to nuclear energy generation in the United States. The authors contended that the functional structure of the designated model and the incorporation of energy pricing are significant factors to consider when evaluating the efficacy of different energy sources. In a study conducted by Beak (2016), the efficacy of nuclear energy use in mitigating GHG emissions within the United States was examined through the manipulation of income and energy consumption variables. The study revealed that the utilization of nuclear energy leads to a reduction in GHG emissions both in the immediate and extended periods. In a recent investigation conducted by Kartal et al. (2023), an examination was undertaken to assess the impact of transitioning between nuclear and renewable energy sources on CO_2 emissions inside the United States. The findings indicate that both nuclear and renewable energy sources have positive impacts on the environment.

In their study, Omri and Saadaoui (2023) employed the non-linear ARDL approach to examine the effects of nuclear energy, fossil fuels, income, and trade on carbon emissions in France for the period spanning from 1980 to 2020. The assessment of the EKC assumption's significance was also conducted. The primary discovery of this study is that the utilization of nuclear power in France effectively reduces the nation's carbon emissions. Nevertheless, the utilization of fossil fuels and the liberalization of trade further increase these emissions. Nevertheless, the research findings indicate the presence of a curvilinear relationship, specifically an inverse U-shaped pattern, between economic growth and carbon emissions. This provides support for the EKC idea. In their study, Zeraibi et al. (2023) investigated the impact of many factors, such as the utilization of natural gas, nuclear power, democratic governance, and banking accessibility, on France's energy self-sufficiency and carbon emissions. The empirical findings derived from the ARDL model suggest that nuclear power, natural gas, and the provision of financial services exhibit an adverse influence on the environment. Nevertheless, it is worth noting that both nuclear power and democratic governance contribute to the mitigation of energy-related hazards, albeit at the expense of increased pricing. Moreover, the outcomes of the study provided support for the U-shaped EKC theory.

The primary focus of research on nuclear energy usage in India revolves around its implications for economic activities. The existing body of research fails to adequately address the interconnectedness between nuclear energy generation and environmental degradation. In their study, Rani and Kumar (2017) utilized an ARDL model to examine the impact of nuclear energy consumption on air pollution reduction in India. Their findings indicate that nuclear energy consumption exhibits a superior performance in mitigating air pollution levels in the country. The researchers' findings presented empirical evidence that supports the recommendation for policymakers to consider substituting fossil fuel usage with nuclear energy sources. In their study, Danish et al. (2021) presented empirical support for the positive impact of nuclear energy production on sustainable economic growth. The researchers expressed their support for the Indian government's efforts to promote electricity generation using nuclear power. Furthermore, the study conducted by Syed et al. (2021) employed the ARDL methodology to examine the disparate impacts of nuclear power and economic growth on carbon dioxide emissions in India from 1975 to 2018. The utilization of nuclear energy as a substitute for fossil fuels in India resulted in a reduction of CO_2 emissions.

The existing body of literature illustrates that the contribution of nuclear energy generation in reducing GHG emissions is subject to varying outcomes across different countries. Hence, an opportunity exists to make a valuable contribution to the current discourse through the application of contemporary methodological approaches. India is allocating increased resources towards renewable and nuclear energy sources with the aim of reducing its reliance on fossil fuel imports and enhancing its energy security. There is a scarcity of scholarly inquiry examining the impacts of nuclear energy utilization on the environmental condition in India through the lens of the EKC framework. Consequently, the primary objective of this research is to address a gap in the existing body of knowledge by examining the influence of nuclear energy on a nation's GHG emissions, specifically within the framework of the EKC hypothesis.

3. METHODOLOGY

3.1. Data

With the aim of examining the impact of nuclear energy use on environmental deterioration in India, this investigation utilized annual data spanning from 1969 to 2021. To assess the extent of environmental degradation, this study utilized GHG emissions as an indicator, quantified in metric tons. Additionally, the independent variables employed in our study were GDP (measured in current US dollars) and nuclear energy usage (measured in joules). The data pertaining to GHG emissions were obtained from the "Our World in Data" database. The data pertaining to economic growth were obtained from the World Development Indicator (WDI) database. The data pertaining to nuclear energy use were obtained from the "Statistical Review of World Energy Data." Figure 2 illustrates the yearly patterns of the variables under investigation. The data indicates a consistent upward trajectory for all variables during the observed time period. In order to assure the smoothness of the data, the variables were converted into their logarithmic form.

3.2. Econometric Model Generation

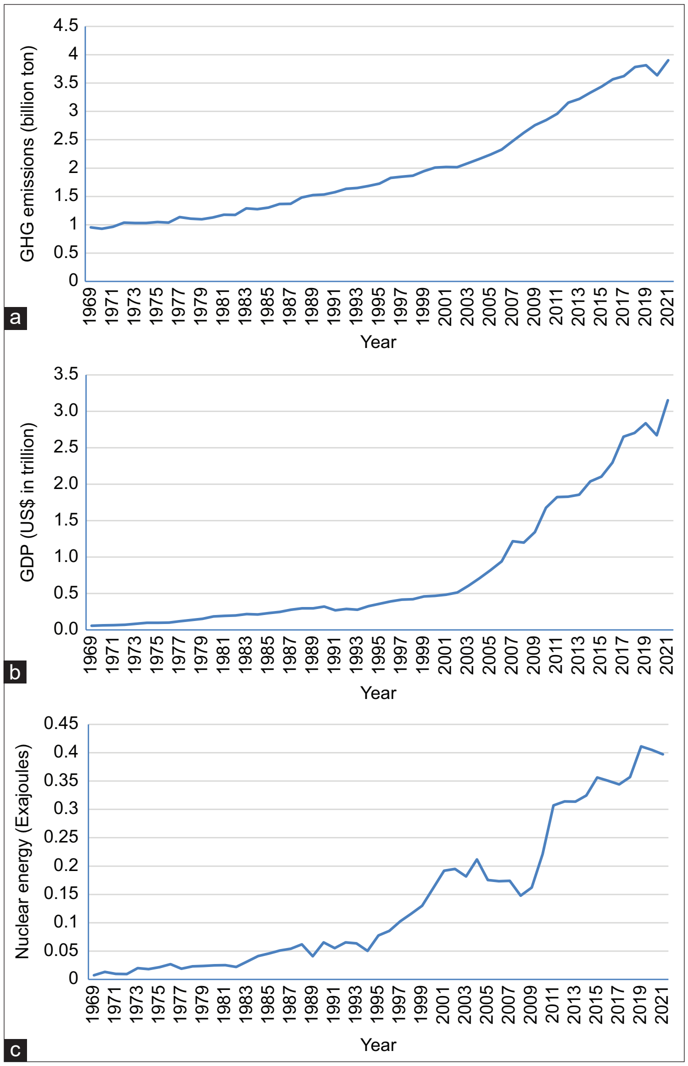
This study aimed to examine the relationship between nuclear energy usage and GHG emissions using the EKC model. As a result of this phenomenon, the model can be mathematically represented by Equation (1):

$$G_t = f\,(Y_t, Y^2_t, N_t) \tag{1}$$

where, G_t is GHG emissions at time t, Y_t is economic growth (GDP) at time t, Y^2_t is the square of GDP at time t, and N_t is nuclear energy use at time t.

The rationale for incorporating the square of economic growth into the model was to investigate the possibility of a negative

Figure 2: Annual trends of the study variables (a) GHG emissions (b) Economic growth (c) Nuclear energy consumption



correlation between this factor and GHG emissions. The empirical evidence reveals a negative correlation between the square of GDP and CO_2 emissions, implying that once a certain threshold of economic development is reached, further economic growth would result in a decline in carbon emissions. This discovery offers empirical evidence that lends credence to the validity of the EKC theory within the particular framework of India. The following is the presentation of the econometric model formulation for the current inquiry:

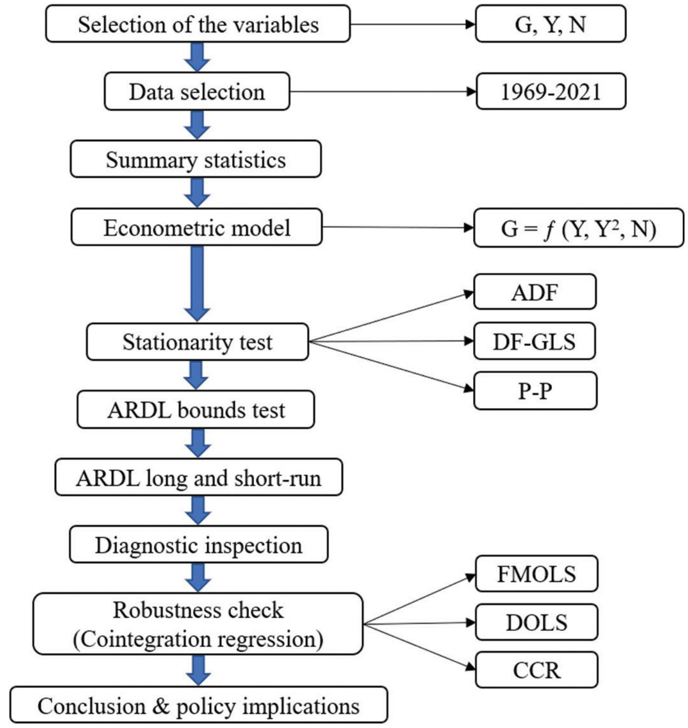
$$G_t = \tau_0 + \tau_1 Y_t + \tau_2 Y^2_t + \tau_3 N_t + \varepsilon_t \quad (2)$$

Where τ_1, τ_2, and τ_3 represent the coefficients of the regressors. Additionally, τ_0 denotes intercept, and ε_t is the error term. Furthermore, it is possible to express Equation (2) in logarithmic form in the following manner:

$$LG_t = \tau_0 + \tau_1 LY_t + \tau_2 LY^2_t + \tau_3 LN_t + \varepsilon_t \quad (3)$$

The flowchart of the analysis is presented in Figure 3.

Figure 3: The analysis flowchart



3.3. Unit Root Tests for Data Stationarity

In order to mitigate the impact of a potentially deceptive regression analysis, it is imperative to do a stationarity test. The methodology ensures that the series under consideration exhibit stationarity, and provides an estimation of the regression equation using stationary techniques. The empirical inquiry provides evidence for the significance of establishing the integration strategy before delving into the topic of cointegration. The literature has proposed several stationarity tests to determine the integration order of a series, as the validity of unit root testing is influenced by the changing sample size (Raihan and Tuspekova, 2022c). In this study, the Augmented Dickey-Fuller (ADF) test developed by Dickey and Fuller (1979), the Dickey-Fuller generalized least squares (DF-GLS) test proposed by Elliott et al. (1996), and the Phillips-Perron (P-P) test introduced by Phillips and Perron (1988) were employed to assess the stationarity of the data.

3.4. ARDL Method

This study employed the ARDL bounds testing approach, as established by Pesaran et al. (2001), to ascertain the presence of cointegration among the variables. The present methodology exhibits numerous advantages in comparison to the preceding approaches employed for cointegration analysis (Raihan and Tuspekova, 2022d). For example, it is relevant in any case involving the integration of investigative series. Furthermore, the identification of the integration property of a series was required prior to the utilization of other cointegration processes. However, this particular method did not impose the necessity for any preceding testing of this nature. In addition, the incorporation of the lag length of the variable allows for the utilization of the ARDL model, which effectively addresses the issue of endogeneity. According to Pesaran et al. (2001), the ARDL model remains viable even when the number of observations is limited. The ARDL bound testing approach can be formulated with the econometric model as depicted in Equation (4):

$$\Delta LG_t = \tau_0 + \tau_1 LG_{t-1} + \tau_2 LY_{t-1} + \tau_3 LY_{t-1}^2 + \tau_4 LN_{t-1} + \sum_{i=1}^{q}\gamma_1 \Delta LG_{t-i} + \sum_{i=1}^{q}\gamma_2 \Delta LY_{t-i} + \sum_{i=1}^{q}\gamma_3 \Delta LY_{t-i}^2 + \sum_{i=1}^{q}\gamma_4 \Delta LN_{t-i} + \varepsilon_t \quad (4)$$

where q is the optimum lag length and Δ is the first difference operator.

The ARDL approach, as proposed by Pesaran et al. (2001), was employed in this work to examine the interaction among several components, considering both the long-term and short-term dynamics. After establishing the presence of cointegration among the parameters being examined, Equation (4) was employed in order to forecast the ARDL estimate for the long-run coefficient. The study examined the short-term dynamics of the variables, as well as the rate at which they adjusted in the short term towards the long-term rate. This was done by utilizing an approximation of the error correction term (ECT) which was employed to forecast the short-term dynamic parameters based on the long-term estimates. In order to accomplish this, the present study integrated the ECT into the ARDL framework, as depicted in Equation (5):

$$\Delta LG_t = \tau_0 + \tau_1 LG_{t-1} + \tau_2 LY_{t-1} + \tau_3 LY_{t-1}^2 + \tau_4 LN_{t-1} + \sum_{i=1}^{q}\gamma_1 \Delta LG_{t-i} + \sum_{i=1}^{q}\gamma_2 \Delta LY_{t-i} + \sum_{i=1}^{q}\gamma_3 \Delta LY_{t-i}^2 + \sum_{i=1}^{q}\gamma_4 \Delta LN_{t-i} + \theta ECT_{t-1} + \varepsilon_t \quad (5)$$

where θ is the ECT's coefficient.

3.5. Robustness Check

In order to assess the durability of the ARDL results, this study employed alternative cointegration regression techniques, namely the fully modified OLS (FMOLS) method developed by Hansen and Phillips (1990), the Dynamic OLS (DOLS) approach proposed by Stock and Watson (1993), and Park's (1992) Canonical Cointegrating Regression (CCR). Through the analysis of serial correlation, these methodologies enable the determination of asymptotic coherence (Raihan and Tuspekova, 2022e; Raihan, 2023c). The FMOLS, DOLS, and CCR methodologies can only be applied when there is evidence of cointegration among the series. The FMOLS, DOLS, and CCR estimation methods are employed for the purpose of evaluating long-term elasticity through the utilization of Equation (4).

4. RESULTS AND DISCUSSION

Table 1 displays the descriptive statistics of the factors examined in the study. The outcomes of several normality tests are presented in conjunction with a comprehensive portrayal of the data. The dataset comprises 53 observations for each variable, encompassing time series data ranging from 1969 to 2021 within the context of India. The sample's variables demonstrate similarity in terms of their mean and median values, indicating the potential presence of normality. Furthermore, it is evident that the dataset exhibits normality as indicated by the skewness values being close to zero. Furthermore, it can be observed that the distribution of data pertaining to GHG emissions and economic growth has a positive skewness, indicating a tendency towards higher values. Conversely, the data related to nuclear energy displays a negative skewness, suggesting a propensity towards lower values. Variables with kurtosis values below 3 are said to have platykurtic characteristics. The normal distribution of all variables is proven by the Jarque-Bera test and associated probability values.

The primary objective of this study was to examine the establishment of a durable association between the series under examination. The assessment of the unit root test is essential for determining the integration properties of the parameters, which is a prerequisite for utilizing the methodologies in establishing long-term interconnections. Hence, an examination was conducted on the integration properties of the series by employing a set of unit root tests, such as the ADF, DF-GLS, and P-P tests. The results of the unit root tests are presented in Table 2. Based on the canonical unit root tests, it was observed that all variables initially displayed the absence of a unit root at the level, but became stationary after undergoing first differencing.

This study determined that the series being analyzed possesses an integrated of order one (I(1)) based on the observations of unit roots. Hence, the present study employed the ARDL bounds test approach to assess the long- and short-term linkages between the variables under scrutiny. The analysis ultimately determined the appropriate lag specification based on the consistent results obtained from each alternative's information criterion. Table 3 presents the results of the cointegration study, indicating that the computed F-statistic (8.29) above the upper critical threshold, signifying statistical significance. Hence, it may be inferred from this analysis that there exists cointegration between the independent variable and the regressors.

Table 4 displays the results of the analysis conducted using the ARDL model, showcasing both the immediate and lasting effects of the variables under examination. The empirical findings indicate that all of the coefficients have statistical significance. The positive coefficients of LY indicate that there is a positive relationship between economic growth and GHG emissions. Specifically, a 1% increase in economic growth is associated with a 1.55% increase in GHG emissions in the long-run, and a 1.15% increase in the short-run. Nevertheless, it is noteworthy that the coefficients associated with LY^2 exhibit negative values in both the long-run and short-run contexts. This implies that a 1% augmentation in

Table 1: Statistical summaries of the variables

Variables	LG	LY	LY^2	LN
Mean	21.315	26.797	719.41	38.918
Median	21.269	26.610	708.10	38.893
Maximum	22.084	28.779	828.20	40.558
Minimum	20.652	24.791	614.61	36.541
SD	0.4459	1.1638	62.572	1.1528
Skewness	0.2403	0.1372	0.1967	−0.2302
Kurtosis	1.8144	1.9502	1.9427	1.8934
Jarque-Bera	3.6138	2.5998	2.8103	3.1725
Probability	0.1642	0.2726	0.2453	0.2047
Observations	53	53	53	53

Table 2: Unit root test results

Logarithmic form of the variables	ADF		DF-GLS		PP	
	Log levels	Log first difference	Log levels	Log first difference	Log levels	Log first difference
LG	0.774	−9.136***	0.540	−5.907***	0.774	−9.181***
LY	−0.314	−6.762***	2.842	−6.833***	−0.322	−6.777***
LY^2	0.002	−6.774***	2.972	−6.844***	−0.017	−6.789***
LN	−1.589	−10.32***	0.427	−5.899***	−1.734	−10.33***

***P<0.01

Table 3: ARDL bounds test results

F-bounds test		Null hypothesis: No degrees of relationship		
Test statistic	Estimate	Significance	I (0)	I (1)
F-statistic	8.287371	At 10%	2.37	3.20
K	3	At 5%	2.79	3.67
		At 2.5%	3.15	4.08
		At 1%	3.65	4.66

Table 4: ARDL long and short-run results

Variables	Long-run			Short-run		
	Coefficient	t-Statistic	P-value	Coefficient	t-Statistic	P-value
LY	1.5493***	2.9385	0.0062	1.1492***	3.0968	0.0034
LY^2	−0.0451***	−3.3058	0.0051	−0.0032***	−3.1117	0.0016
LN	−0.1619***	−4.6094	0.0075	−0.0196***	−4.1273	0.0051
C	24.671	1.5154	0.1127	-	-	-
ECT (-1)	-	-	-	−0.7861***	−4.3253	0.0003
R^2	0.9980					
Adjusted R^2	0.9873					

***P<0.01

the square of economic growth would result in a reduction of GHG emissions by 0.05% in the long-run and 0.003% in the short-run. This implies that the coefficients of income variables exhibit alternating signs, which serves as evidence supporting the EKC hypothesis for India, both in the long-term and short-term. Hence, there exists an inverted U-shaped link between the level of economic growth and GHG emissions. Therefore, it appears that the EKC hypothesis holds true for all pertinent implications within the context of the Indian economy. It may be inferred that the increase in economic levels has varying effects on air pollution indicators across different stages of India's economic development. While it is true that there is a correlation between economic growth and environmental deterioration up to a certain point, it should be noted that beyond this threshold, further increases in wealth actually contribute to an improvement in environmental quality. The current study's results about the presence of the EKC phenomenon in India are corroborated by the research conducted by Rasool et al. (2020), Mahmood et al. (2021), Jena et al. (2022), Murshed and Dao (2022), Mehmood et al. (2022), Adebayo et al. (2023), and Uche et al. (2023).

Moreover, it can be observed that the utilization of nuclear energy is associated with a notable decrease in air pollution, as indicated by the significantly negative coefficient of LN. In a more scholarly manner, the findings suggest that a marginal increase of 1% in the utilization of nuclear energy leads to a reduction of GHG emissions by around 0.02% in the immediate term and 0.16% in the long term. The empirical findings pertaining to India indicate that the utilization of nuclear energy as a means of electricity generation presents a viable approach for addressing environmental deterioration and ameliorating the adverse impacts of energy consumption on both climate change and sustainable development. Nuclear energy generation presents itself as a viable and environmentally friendly means of energy production, offering the potential for sustained economic development. Hence, our findings underscore the need for politicians to advocate for increased investments in nuclear energy generation as a means of safeguarding the environment.

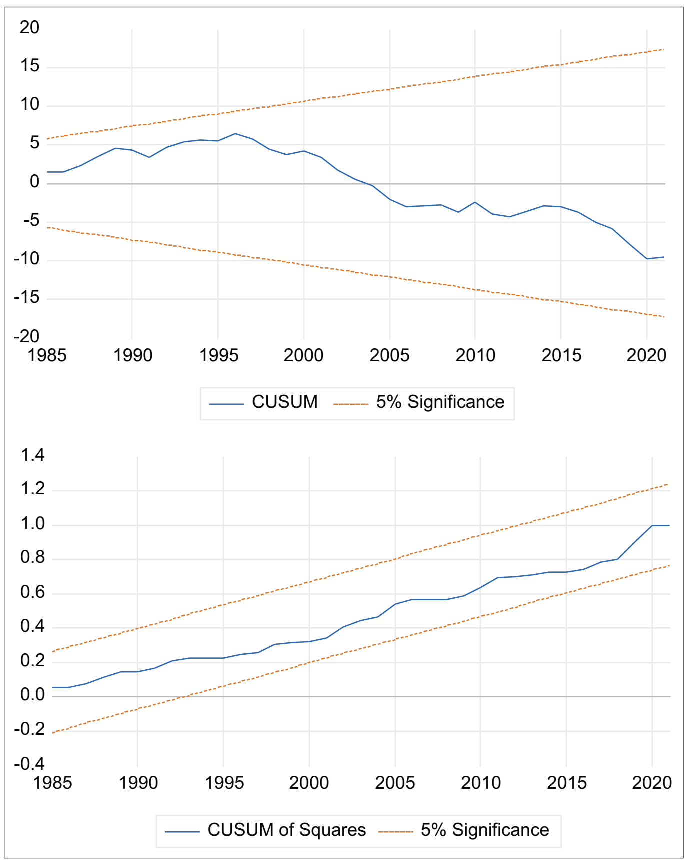
The results indicating a negative correlation between nuclear energy and GHG emissions in India align with the conclusions of previous studies conducted by Rani and Kumar (2017), Danish et al. (2021), and Syed et al. (2021). Additionally, our research aligns with multiple studies that have presented empirical support for the inverse correlation between the utilization of nuclear energy and the occurrence of environmental pollution across various nations globally. For example, Hassan et al. (2020) for BRICS countries; Piłatowska et al. (2020) for Spain, Saidi and Omri (2020) for OECD countries; Azam et al. (2021) for the ten highest CO_2 emitting counties; Jahanger et al. (2023) for top nuclear energy countries; Zeraibi et al. (2023) for France; Kartal et al. (2023) in the United States; and Sadiq et al. (2023) in the top ten countries with the highest nuclear energy consumption.

In addition, it is noteworthy that both the long-run estimation R2 and the adjusted R2 exhibit values of 0.9980 and 0.9873, respectively. These values suggest that the regression model created demonstrates a high degree of fit with the data. This would suggest that the variations in the dependent variable can be comprehensively accounted for by the independent factors. Furthermore, given the statistically significant and negative coefficient of the ECT indicating that the error correcting mechanism is operational. The coefficient of the ECT (0.786) suggests that around 78.6% of the deviations from GHG emissions will be rectified during a one-year period, indicating a relatively rapid return to equilibrium.

There are several Diagnostic tests were employed to assess and substantiate the viability of the model. Table 5 displays the results of the diagnostic testing. The findings indicate that the anticipated model has satisfactory levels of autocorrelation, normality, shifting variance, and model-building error. Furthermore, this study conducted stability assessments for the projected long-term model through the utilization of the cumulative sum of recursive residuals (CUSUM) and the squares of CUSUM (CUSUMQ). Figure 4 illustrates the outcomes of the CUSUM and CUSUMSQ tests. The presented graphs indicate that the proposed model exhibits stability during the relevant time frame, as evidenced by the residuals remaining within the critical boundaries established at a significance level of 5%.

The validity of the long-term estimation obtained by the ARDL technique was assessed by employing the FMOLS, DOLS, and CCR tests. The estimated results obtained by the utilization of FMOLS, DOLS, and CCR techniques are presented in Table 6. The findings of this study demonstrate that the FMOLS, DOLS, and CCR estimators exhibit consistent and reliable performance. Consequently, this leads to the generation of identical outcomes as observed in the long-term ARDL simulations. The findings indicate that a progressive adoption of nuclear energy would lead to a reduction in GHG emissions over an extended period of time. Furthermore, the presence of positive coefficients for LY and negative coefficients for LY^2 in all three models provides evidence supporting the validity of the EKC hypothesis. Therefore, the findings of the FMOLS, DOLS, and CCR models are consistent with the results obtained from the ARDL analysis. Moreover, the elevated values of R2 and the modified R2 indicate the precision of the estimation.

Figure 4: Plot of CUSUM and CUSUMQ tests



The recent era has witnessed a notable growth in energy demand due to the concurrent rise of industrialization and globalization on a worldwide scale (Raihan et al., 2022a). The proliferation of fossil fuel utilization has resulted in significant detrimental impacts on the environment. The use of fossil fuels has led to a notable rise in GHG emissions, hence contributing to environmental strain (Raihan et al., 2022b). The escalation of environmental deterioration has prompted a heightened recognition of the natural world, leading countries to adopt clean energy sources in order to fulfill their energy requirements (Raihan et al., 2022c). Nuclear energy is employed as a clean energy source to mitigate GHG emissions (Sadiq et al., 2023). Despite the safety risks associated with the establishment of large-scale nuclear power plants, numerous industrialized and developing countries have witnessed a significant boost in their electricity generation by adopting nuclear energy sources (Adebayo et al., 2023). Nuclear power facilities appear to produce electricity in a manner that is more ecologically sustainable. Consequently, although nuclear power facilities necessitate greater financial investments, they effectively mitigate environmental degradation and stimulate cleaner economic activity, unlike fossil fuels (Zeraibi et al., 2023).

The study conducted by Kartal et al. (2023) presents empirical evidence that aligns with the perspective advocating for an expansion of nuclear energy production as a means to mitigate the adverse consequences associated with the emission of GHGs, which are recognized as significant drivers of global warming and climate change. According to Omri and Saadaoui (2023), promoting the consumption of nuclear energy could contribute to sustainable economic growth by providing energy security for countries that rely heavily on energy resources. Nevertheless, the implementation of nuclear power plants and the utilization of radioactive materials for energy production entail certain hazards (Danish et al., 2021). Hence, it is imperative to exercise caution and prioritize safety when undertaking new investments and establishing nuclear power facilities.

Table 5: Diagnostic tests results

Diagnostic tests	Coefficient	P-value	Decision
Breusch-Godfrey serial correlation LM test	0.3362	0.7168	No serial correlation exists
Breusch-Pagan-Godfrey heteroscedasticity test	0.7583	0.6871	No heteroscedasticity exists
Jarque-Bera test	2.2378	0.3266	Residuals are normally distributed
Ramsey RESET test	0.9971	0.4349	The model is properly specified

Table 6: Robustness tests results

Variables	FMOLS		DOLS		CCR	
	Coefficient	t-Statistic	Coefficient	t-Statistic	Coefficient	t-Statistic
LY	1.5486***	2.9563	1.4864***	2.7826	1.5723***	3.0847
LY^2	−0.0328***	−3.4970	−0.0324***	−3.3865	−0.0333***	−3.6454
LN	−0.1666***	−4.3129	−0.1604***	−3.2051	−0.1685***	−4.1917
C	32.672	4.9593	32.770	4.9252	32.951	5.2257
R^2	0.9874		0.9877		0.9874	
Adjusted R^2	0.9867		0.9869		0.9866	

***P<0.01

India has successfully established a nuclear power program that primarily relies on domestically developed technologies and resources (Adebayo et al., 2023). The commitment of the Indian government to augment its nuclear power capacity has been substantiated, since it forms an integral part of their comprehensive infrastructure development endeavor. The administration has set ambitious goals to enhance nuclear capability. Nuclear energy represents a notable component of India's power generation, ranking as the fifth most substantial contributor. It contributes approximately 3% to the overall electricity production in the country. India is home to a comprehensive network of 22 nuclear reactors, strategically located throughout 7 power stations around the country. These reactors collectively contribute to India's overall nuclear power generation capacity, which currently stands at an impressive 7380 MW. India is presently engaged in the construction of six new nuclear power stations, augmenting the existing seven operational plants. These forthcoming installations are anticipated to possess a combined capacity of 9.4 GW. Moreover, the government of India has devised strategies to establish an additional eight nuclear power plants, with a combined capacity of 31,000 MW. In April 2023, the Indian government issued a formal statement outlining their plans to enhance their nuclear power generation capacity to 22.5 GWe by the year 2031. The proposed ambitious initiative is to facilitate the integration of nuclear energy into India's overall electricity generation, with the objective of accounting for around 9% of the country's total electricity production by the year 2047. India is currently engaged in proactive efforts to seek nuclear investments as a means to mitigate the scarcity of fossil resources and fulfill its electricity requirements. To adequately address climate-related concerns, it is crucial to embrace a path towards achieving carbon neutrality. This necessitates the simultaneous promotion of nuclear energy, as well as the development and utilization of wind and solar power sources. The collaborative endeavor will lay the groundwork for a future that is both promising and sustainable.

5. CONCLUSION AND POLICY IMPLICATIONS

The main objective of this study is to examine the influence of nuclear energy consumption and economic growth on GHG emissions in India from 1969 to 2021. The findings from the ADF, DF-GLS, and P-P unit root tests provided evidence supporting the presence of data stationarity. Furthermore, the findings of the ARDL bounds test revealed a cointegrating relationship between nuclear energy use, GHG emissions, and GDP. The ARDL calculation conducted in this study demonstrates a significant negative correlation between the utilization of nuclear energy and GHG emissions. This finding suggests that the upward trajectory in nuclear energy consumption contributes to the enhancement of environmental conditions by effectively mitigating GHG emissions, both in the short- and long-term. Furthermore, the presence of a notably positive coefficient for economic growth and a notably negative coefficient for the squared value of economic growth offers empirical support for the EKC hypothesis within the context of India. The efficacy of the ARDL model in estimating both long- and short-run relationships was validated through the utilization of the FMOLS, DOLS, and CCR methodologies. The study findings indicate a recommendation for policymakers to enact innovative environmental policies that encourage the development and responsible utilization of nuclear energy, given its greater environmental cleanliness in comparison to fossil fuels. This transformation not only serves to alleviate the economic burden and reduce excessive dependence on oil, but also promotes sustained economic development in the long run.

The findings of this study offer support for the potential of nuclear energy as a viable and environmentally friendly alternative to foster long-term economic growth and environmental sustainability in India. The aforementioned findings have the potential to have significant ramifications for policymakers across various domains. Expanding the capacity of nuclear power plants is of paramount importance in the pursuit of sustainable and environmentally friendly economic development. It is imperative for the Indian government and policymakers to prioritize the substantial utilization of nuclear power in meeting their energy demands. Nuclear energy exhibits a notably higher level of environmental cleanliness when compared to alternative energy sources, such as fossil fuels. Furthermore, it is imperative for politicians to enact novel ecological policies and augment investments in nuclear energy in order to effectively mitigate GHG emissions and address the pressing issue of environmental deterioration. Given its potential to decrease dependence on imported oil and petroleum products, as well as enhance the prevailing balance sheet, nuclear energy holds promise as a viable mechanism for fostering long-term economic growth. The utilization of nuclear energy in the generation of electricity will additionally contribute to ensuring energy security for India. Consequently, India experiences a diminished impact from prospective global instabilities pertaining to energy production and commerce. Hence, it is imperative for policymakers to establish a system of incentives that promotes the development and consumption of nuclear energy. On the other hand, it is imperative for policymakers to possess an understanding of the possible hazards and security concerns associated with the development of nuclear electricity. Hence, it is imperative for policymakers to implement security measures within nuclear power facilities as a means of averting potential catastrophes.

The present study is centered on the linear analysis of the relationship between nuclear energy and GHG emissions. However, it is important to acknowledge that there are certain limitations associated with our research. Hence, additional investigation may be conducted to explore the non-linear aspects pertaining to the contribution of nuclear energy generation in the context of environmental conservation. Moreover, it is suggested that future studies could employ advanced econometric techniques to compare the results of individual countries with the overall outcomes of the panel. This would complement the existing panel estimations and provide a more comprehensive analysis. These sources have the potential to offer valuable insights and comparisons to the results of this study, so contributing to the existing body of knowledge in a meaningful way.

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