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# Measuring the Impact of Technology Innovations and Renewable Energy Consumption for Enhancing Environmental Sustainability in India: Empirical Evidence from ARDL Approach

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## Abstract

Rising carbon dioxide ($CO_2$) emissions at a breakneck pace are a serious problem for sustainable development. To ensure climate-protected sustainable development, advocacy for the advancement of secure and environmentally friendly energy sources for the future is necessary. The generation and use of renewable energy are crucial in this situation. In addition, technological innovation is essential to experiencing the advantages of renewable energy and lowering the release of various harmful gases. Against this backdrop, this study intends to investigate the contribution of technological innovation along with the use of renewable energy in ensuring environmental sustainability in India using the ARDL model. Further, the Granger causality test is also performed in this study to check the direction of causality among the variables. The study's findings highlighted two distinct effects of technological innovation and the consumption of renewable energy on the environment. A positive association is reported between technological innovation and $CO_2$ releases. This may imply that innovation in technology in India is unable to act as an instrument to bring about environmental sustainability. On the other hand, a negative relationship is reported between renewable energy consumption and $CO_2$ releases in India in both the short and long run. This means that using renewable energy would help India achieve environmental sustainability by reducing $CO_2$ releases.
***Keywords**: ARDL; $CO_2$ Emissions; Renewable Energy; Sustainable Development; Technological Innovation*

***JEL Classifications:*** *C12, C18, Q2, Q56*

## Introduction

The quality of the environment acts as a crucial parameter in ensuring the sustainable future of the world. Rising carbon dioxide ($CO_2$) emissions at a breakneck pace are a serious threat to sustainable development (Dang *et al.,* 2021). To resolve several major global issues and safeguard the earth from the red eyes of environmental degradation, the Sustainable Development Goals (SDGs) were introduced by the United Nations in 2018. However, the worldwide effort to achieve those SDGs is being hampered by the acceleration of various

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industrial activities, non-renewable energy-driven economic expansions, and rising environmental degradation. Additionally, the alarming findings provided by various national- and international-level reports have sparked doubts about the world's ability to accomplish the SDGs within the allotted time frame and questioned whether the world is in the proper direction to meet the global goal of zero carbon emissions. The "World Energy Investment Report" published in 2021 by the IEA highlights that during the upcoming two decades, $CO_2$ emissions by several developing and emerging economies are going to rise significantly (i.e., by five gigatons). Furthermore, according to the UN's report on "Progress Towards the Sustainable Development Goals," the frequency of medium- to severe-scale disasters such as floods, storms, heat waves, and wildfires is expected to rise by 40% by the year 2030, which is the deadline year of SDGs. Thus, more attention is required to stop the rising amount of $CO_2$ emissions in order to promote environmental quality, better public health, and sustainable and inclusive economic growth. In this perspective, the adoption of renewable energy is considered an essential alternative method for reducing environmental damage and achieving the SDGs (Odugbesan & Aghazadeh, 2021).

However, emerging economies have made great strides in terms of their financial development. In order to fulfill their energy requirements, emerging economies mostly rely on the usage of fossil fuels, which are responsible for two-thirds of global greenhouse gas (GHG) emissions (International Monetary Fund, 2022). Notably, only six emerging economies, including BRICS countries except Russia, Indonesia, and Mexico, collectively consume a significant portion (one-third portion) of the world’s energy (International Energy Agency, 2023). On the flip side, despite being the third-largest energy customer in the globe, different conventional sources such as coal, oil, etc. still fulfill a major portion (i.e., 80%) of India's energy requirements (India Energy Outlook, 2021). India has introduced several energy efficiency and energy transition-oriented policies and programs to promote a safe and sustainable energy future. Since 2015, there has been tremendous progress in the installation of renewable energy, particularly solar energy. India's installed solar capacity increased by around five times in just four years, i.e., from 2015 to 2019 (India Energy Outlook, 2021). Additionally, India aimed to generate around fifty percent of its existing electric power capacity from environmentally friendly non-fossil fuel sources by 2030, which is the target year of the SDGs. As of December 31, 2022, 167.75 GW of non-fossil fuel-based renewable energy capacity had been deployed nationwide, while 78.75 GW of projects were in various phases of development in India (Yearly Report published by the Ministry of New and Renewable Energy, GOI 2022–23). As a result, India placed fifth and scored high marks in the GHG emissions and renewable energy categories of the Climate Change Performance Index, 2023. Despite these efforts, India is positioned 3rd in the list of the most carbon-emitting countries on the globe. Still, residents of various Indian cities inhale very poor-quality air. It is also true that the industrial revolution and subsequent technological developments have brought about a number of economic and environmental changes in the modern world, such as rising living standards, emerging economies, and a greater reliance on conventional energy. India has to deal with serious industrial pollution of the environment. This is a vital time for taking active action to reduce carbon emissions to enhance environmental sustainability in India and adopting environmentally friendly technologies to achieve the target of carbon neutrality by the end of 2030 (Liu & Lee, 2020). The state of the environment has an irreversible effect on Indian citizens' lives. It is also imperative to look into how India's use of renewable energy sources and technological advancements affects environmental sustainability since environmental sustainability has historically been a key component of long-term development goals and is a challenge that developing nations must contend with. Due to this, this study examines the relationship between environmental sustainability, the usage of renewable energy, and technological advancements. It also presents fresh research that adds to the body of knowledge and could be especially useful to the nation's policymakers in their efforts to promote environmental sustainability.

The remaining portion of the study is organized as follows: Section 2 deals with the review of the existing literature along with the identification of the research gap; Section 3 discusses the objective of the study; Section 4 highlights the research methodology; Section 5 highlights the results and discussions; Section 6 appends the conclusion; and Section 7 displays the policy implications of the study.

**Review of Literature**

Several countries experienced economic prosperity due to their higher level of industrialization. But in most cases, this industrialization provokes several environmental issues. The first phase of the Environmental Kuznets Curve also argues that the economic growth of any nation brought about by rapid industrial development adversely affects the quality of the environment (Leal & Marques, 2022). Various studies have also examined the influence of rapid industrial and economic development on the environment. However, for any country, specifically for developing countries, industrial development is of utmost importance for its economic prosperity and to address various social issues such as poverty, hunger, unemployment, etc. But in most cases, this industrial development puts so much stress on the environment by exacerbating different GHGs. However, like land, labour, capital, and entrepreneurs, energy is also a critical factor for the industrial development of any country. But still, most countries rely on conventional, non-renewable energy resources for their energy requirements. Studies by Nathaniel & Iheonu (2019); Anwar *et al*. (2021)*;* and Rahman & Alam (2022) depicted how industrialization and non-renewable energy use accelerate carbon releases in different regions of the globe. Here comes the dynamic role of renewable energies, which mitigate environmental issues on the one hand and, on the other hand, ensure the flow of economic growth. In this regard, several earlier studies recognized the favourable influence of renewable energy on the environment. Bilgili, Koçak, & Bulut (2016) considered the data from 17 OECD countries during 1977–2010 to assess the effect of the adoption of renewable energy on carbon pollution using various panel estimation techniques. Results found that renewable energy consumption had an adverse effect on carbon emissions in OECD countries. The study by Nguyen & Kakinaka (2019) found that the influence of renewable energy on the level of carbon emissions differed among various groups of countries from 1990 to 2013. They reported that in low-income countries, the usage of renewable energy enhances carbon emissions. In contrast, the results of the co-integration analysis reported that for high-income countries, the adoption of renewable energy minimizes carbon pollution. Another study by Dong, Dong & Jiang (2020) also confirms these outcomes. They analyzed 120 countries from 1995 to 2015. The results of this study also reported that the usage of renewable energy minimizes carbon emissions in high- and upper-middle-income nations. Whereas, the mitigation effect is not clearly observed for middle- and lower-income countries. The influence of both renewable as well as conventional energy usage on the environment. Their findings revealed that the adoption of renewable energy helps to heal the environment by minimizing the carbon emissions. In contrast, they found that the usage of non-renewable energy simulates environmental dilapidation by raising carbon emissions in OECD countries (Shafiei & Salim, 2014). The positive impact of renewable energy usage on the environment was identified in a study conducted by Haldar & Sethi (2021), who applied different estimation techniques to analyze the contribution of renewable energy to pollution in 39 developing countries from 1995 to 2017. Their findings suggest that increasing renewable energy consumption plays a crucial role in improving environmental quality by mitigating carbon emissions in the long run. The study of Khan, Oubaih, & Elgourrami (2022) also reported similar types of findings in Morocco during 1985–2020. The results of this study also reported that the use of renewable energy minimizes carbon pollution. On the other hand, the findings of the study by Danish *et al.* (2018) documented the adverse effect of renewable energy production on the quality of the environment. Whereas the study of Bento & Moutinho (2016) found the favorable influence of renewable energy production on the environment, as a higher level of renewable energy production improves air quality in the environment of Italy by mitigating carbon emissions in both the long-run and short-run. In this regard, technological innovation is also considered a vital ingredient in reducing pollution and promoting environmental sustainability. This technological innovation is crucial for both renewable as well as conventional energy resources. It brings energy efficiency to conventional non-renewable energy sources, which further protects the environment by reducing pollution. On the other hand, it provides better technologies to develop renewable energy infrastructure and GHG-free energy alternatives (Chen & Lei, 2018). The effects of the invention of new technologies on the level of carbon pollution in the Next 11 (N-11) economies over the period 1990–2017 The empirical results showed that technological innovation and the use of renewable energy are adversely related to carbon pollution in N-11 countries (Wang *et al.,* 2020). The study of Shan *et al.* (2021) also documented similar sorts of findings. The study by Vural, G. (2021) reported that technological innovations enhance renewable energy production, which further reduces carbon emissions in Latin American countries. The nexus between the usage of renewable energy, technological innovations, and carbon pollution in Malaysia over the period 1990–2019 Their results indicated that both technological innovation and the usage of renewable energy improve the state of environmental quality in Malaysia by reducing carbon emissions (Raihan *et al.,* 2022). Likewise, Lin & Zhu (2019) identified the benefit of the invention of renewable energy technology in reducing $CO_2$ releases as the structure of energy consumption becomes more coal-dominated, but it increases as the share of renewable energy output rises. Zhu *et al.* (2020) confirm that, compared to southern China, the air quality in northern China is typically worse, particularly in Shanxi, Shandong, Hebei, and Henan. Although they have little bearing on sulfur dioxide ($SO_2$), the invention of new technologies in the field of renewable energy sector are helpful in reducing the quantities of nitrogen oxides (NOx) and respirable suspended particles (PM10). By taking into account the aforementioned pertinent factors, He *et al.*'s (2018) study demonstrates that policymakers and industry players comprehend the effective promotion of tires in China.

After consulting several earlier studies on the utilization and production of energy and environmental quality, researchers found that no comprehensive study has been made that assessed the effect of renewable energy intake on environmental sustainability in India using the ARDL model from 1990 to 2020.

## Objective of the Study

In order to address the above-stated research gap, the present study intends to critically analyze the impact of renewable energy usage on environmental sustainability in India using the ARDL model from 1990 to 2020.

## Methodology

This study examines the relationship between renewable energy usage and technological innovation on environmental sustainability in India using annual data from the World Bank (World Development Indicator/WDI) covering the years 1990–2020. Further, this study is carried out following the novelty of the works conducted by Bagchi (2016), Bagchi (2017), Bagchi *et al.* (2020), and Bagchi & Paul (2023).

## Model Specification (Basic Model)

The following basic model is used to analyze the impact of renewable energy usage and technological innovations on environmental sustainability in India.

$CO_2 = f\,(RE, TI)$

Where,

$CO_2$ = Carbon emissions

RE = Renewable energy consumption

TI = Technological Innovation

## Econometric Model

The following econometric model is used here:

$LNCO_{2t} = \beta_0 + \beta_1 LNRE_t + \beta_2 LNTI_t + \varepsilon_t$

Where $LNCO_2$ is the Dependent Variable (DV), *LNRE* is the Independent Variable (IV) and *LNTI* is the Control Variable (CV). $\beta_0$, $\beta_1$, $\beta_2$, ... $\beta_n$ are the model parameters and $\varepsilon_t$ is the disturbance term of the model.

***Table 1: Representation and Description of Selected Variables***

| Variable Code | Variable Description | Proxy Parameter |
|---|---|---|
| $LNCO_2$ | Natural Log of $CO_2$ emissions (metric tons per capita) | Environmental Sustainability (Vo & Vo, 2021; Tiawon & Miar, 2023; Behera, Behera, & Sethi, 2023; Iqbal, Hassan & Arshed 2023) |
| LNRE | Natural Log of Renewable Energy Consumption (proportion of total final energy consumption) | Renewable Energy (Karimi Alavijeh *et al.*, 2023; Behera, Behera, & Sethi, 2023; Huang, Abidin, Raza, 2023) |
| LNTI | Natural Log of patent applications, residents and non-residents | Technological Innovation (Adebayo & Kirikkaleli, 2021; Wu, Cui, & Wang, 2023) |

*Source: (Authors' own compilation) (World Bank, 2023)*

### Econometric Tools Used

At first, a unit root test is performed in this study. Here, researchers relied on the Augmented Dickey-Fuller (ADF) and Philip-Perron (PP) methods to assess the stationarity of the above-mentioned variables. For determining what would be the ideal lag length for an Autoregressive Distributed Lag (ARDL) model, the Akaike Information Criterion (AIC) is utilized here. In order to confirm the long-run co-integrating relationship among the selected variables, the ARDL bound test is used. Further, short-run and long-run estimation techniques are also assessed here. Moreover, the Granger causality test is also performed in this study to check the direction of causality among the variables. This study also applied the Jarque-Bera test for testing residual normality. At last, the constancy of the model is examined through CUSUM and CUSUM of Square (CUSUMSQ) tests.

### Results and Discussion

### Descriptive Statistics

Table 2 highlights the descriptive statistics of the selected variables. The results indicate that for each of the selected variables, there exists a small difference between their mean and median. Further, it is evident that the variables are not more scattered from their average values since the standard deviation statistics are not very high. A further probability value of the Jarque-Bera test displays that the data are normally distributed.

***Table 2: Results of Descriptive Statistics***

| | **$LNCO_2$** | **LNRE** | **LNTI** |
|---|---|---|---|
| Mean | 0.0711 | 3.7310 | 9.7652 |
| Median | -0.0158 | 3.7878 | 10.1016 |
| Maximum | 0.5853 | 3.9693 | 10.9467 |
| Minimum | -0.4347 | 3.4833 | 8.1385 |
| Std. Dev. | 0.3340 | 0.1701 | 0.9792 |
| Skewness | 0.1450 | -0.1899 | 0.3703 |
| Kurtosis | 1.5708 | 1.4517 | 1.6051 |
| Jarque-Bera | 2.7468 | 3.2827 | 3.2217 |
| *p*-value | 0.2532 | 0.1937 | 0.1997 |

*Source: (Researchers' own estimation)*

### Unit Root Test

Researchers have now conducted the unit root test using the ADF and PP approaches to assess the stationarity of selected variables. ADF and PP test outcomes at the 5% level of significance confirm that the data are stationary and free of unit root at the first difference (table 3).

***Table 3: Results of ADF and PP Unit Root Tests***

| Variable | ADF approach | PP approach |
|---|---|---|
| LNCO2 | -2.3012** | -2.2768** |
| LNRE | -3.8842** | -3.7851** |
| LNTI | -4.9364 ** | -5.9278** |

**Significance at 5% level.

*Source: (Researchers' own estimation)*

**ARDL Model Selection**

As the ARDL model includes the lagged values of both dependent and independent variables simultaneously, it is essential to find the appropriate lag length to get a suitable model. The AIC is used here to regulate the appropriate lag length for an ARDL model. The model selection process is summarized in Table 4. Based on AIC, the ARDL (1, 2, 2) model is chosen as the suitable model for the analysis.

***Table 4: Outcomes of the ARDL Optimal Model (1, 2, 2) selected based on AIC***

| Dependent Variable is $CO_2$ | | | |
|---|---|---|---|
| **Independent Variables** | **Coefficient** | **t- Stat.** | **Probability** |
| $LNCO_2$ (-1) | 0.3781 | 2.2955 | 0.0321 |
| LNRE | -1.1983 | -5.6624 | 0.0000 |
| LNRE (-1) | 0.9511 | 2.2170 | 0.0378 |
| LNRE (-2) | -0.7531 | -2.3261 | 0.0301 |
| LNTI | 0.0274 | 1.3892 | 0.1793 |
| LNTI (-1) | -0.0177 | -0.6877 | 0.4992 |
| LNTI (-2) | 0.0290 | 1.3214 | 0.2006 |
| C | 3.4231 | 3.4881 | 0.0022 |
| R-squared | 0.9974 | | |
| Adj. R-squared | 0.9966 | | |
| D-W stat. | 2.1091 | | |
| Probability (*F*-stat.) | 0.0000 | | |

*Source: (Researchers' own estimation)*

***ARDL Bound Test for Cointegration***

***Table 5: Results of the ARDL Bound Test (ARDL (1, 2, 2) selected based on AIC)***

| Statistics | Value | K |
|---|---|---|
| F-stat | **5.3023** | 2 |
| Significance | I(0) | I(1) |
| 10% | 2.63 | 3.35 |
| 5% | 3.10 | 3.87 |
| 2.50% | 3.55 | 4.38 |
| 1% | 4.13 | 5.00 |

*Source: (Researchers' own estimation)*

In order to confirm the long-run co-integrating associations among the study variables, the ARDL bound test is applied here. Results of the ARDL bound test (Table 5) confirmed that variables are co-integrated as the calculated F-stat, i.e., 5.3023, is above the upper bound level, i.e., 5.00, at a 1% level of significance.

**Long-Run Estimation**

***Table 6: Results of Long-run Estimations (ARDL (1, 2, 2) selected based on AIC)***

| **Dependent Variable is $CO_2$** | | | |
|---|---|---|---|
| **Variable** | **Coefficient** | **t-Statistic** | **Prob.** |
| LNRE | -1.6085 | -12.1899 | 0.0000 |
| LNTI | 0.0622 | 2.7068 | 0.0132 |
| C | 5.5043 | 7.7824 | 0.0000 |

*Source: (Researchers' own estimation)*

The long-run coefficients for the selected model are demonstrated in Table 6.

The long-term estimates highlight two distinct effects of technological innovation and the consumption of renewable energy on the environment. Where a positive association is reported between technological innovation and $CO_2$ releases. On the other hand, the usage of renewable energy is reported to have significant adverse impacts on $CO_2$ emissions in the long run in India. $CO_2$ emissions are reduced by 1.60 units for every unit increase in renewable energy usage in the long run, at a 1% level of significance.

**Short-Run Estimation and Error Correction Term**

***Table 7: Results of Short-run Estimations Using the ARDL Approach***

| **Dependent Variable is $CO_2$** | | | |
|---|---|---|---|
| **Variable** | **Coefficient** | **t-Stat.** | **Probability** |
| D (LNRE) | -1.1983 | -6.8949 | 0.0000 |
| D (LNRE (-1)) | 0.7531 | 2.5473 | 0.0188 |
| D(LNTI) | 0.0274 | 1.6989 | 0.1041 |
| D (LNTI (-1)) | -0.0290 | -1.7306 | 0.0982 |
| ECT (-1) | -0.6218 | -4.9233 | 0.0001 |
| **R-squared** | **0.812096** | | |
| **Adjusted R-squared** | **0.780779** | | |

*Source: (Researchers' own estimation)*

The short-run estimations (Table 7) are corroborated with the long-run estimation results. Results imply that the consumption of renewable energy has significant adverse impacts on $CO_2$ emissions in the short run in India. Further, the Error Correction Term (ECT) value fulfills all three standard conditions and is statistically significant, having a negative and < 1 coefficient. The coefficient's value of 0.62 indicates a 62% adjustment towards equilibrium.

Most interestingly, the results of the present study reveal a positive association between technological innovation and $CO_2$ emissions, both in the short and long term. These results also corroborate the empirical studies of Ali *et al.* (2022) and Rahman & Alam (2022). Whereas the study of Raihan *et al.* (2022) documented a not-so-significant association between technological innovation and $CO_2$ emissions.

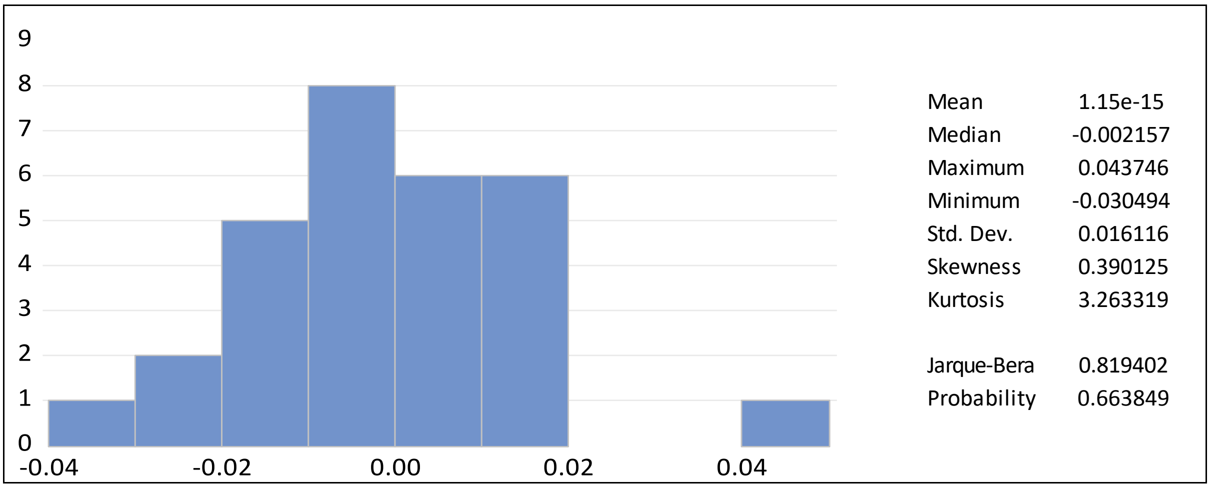
***Table 8: Outcomes of Pairwise Granger Causality Tests***

| Null Hypothesises (NHs) are: | Observation | F-Stat. | Probability |
|---|---|---|---|
| LNRE does not Granger Cause $LNCO_2$ | 30 | 6.19929 | 0.0192 |
| $LNCO_2$ does not Granger Cause LNRE | | 1.27337 | 0.2691 |
| LNTI does not Granger Cause $LNCO_2$ | 30 | 7.67772 | 0.01 |
| $LNCO_2$ does not Granger Cause LNTI | | 0.36124 | 0.5528 |

*Source: (Researchers' own estimation)*

Table 8 presents the outcomes of Pairwise Granger Causality tests. Results indicate the consumption of renewable energy granger causes carbon releases in India. Whereas, carbon emissions do not granger cause the usage of renewable energy. This indicates an upsurge in the adoption of renewable energy will minimize the level of carbon releases in India. On the other hand, the results highlight the existence of a one-way causal relationship between technological innovation to carbon emissions in India.

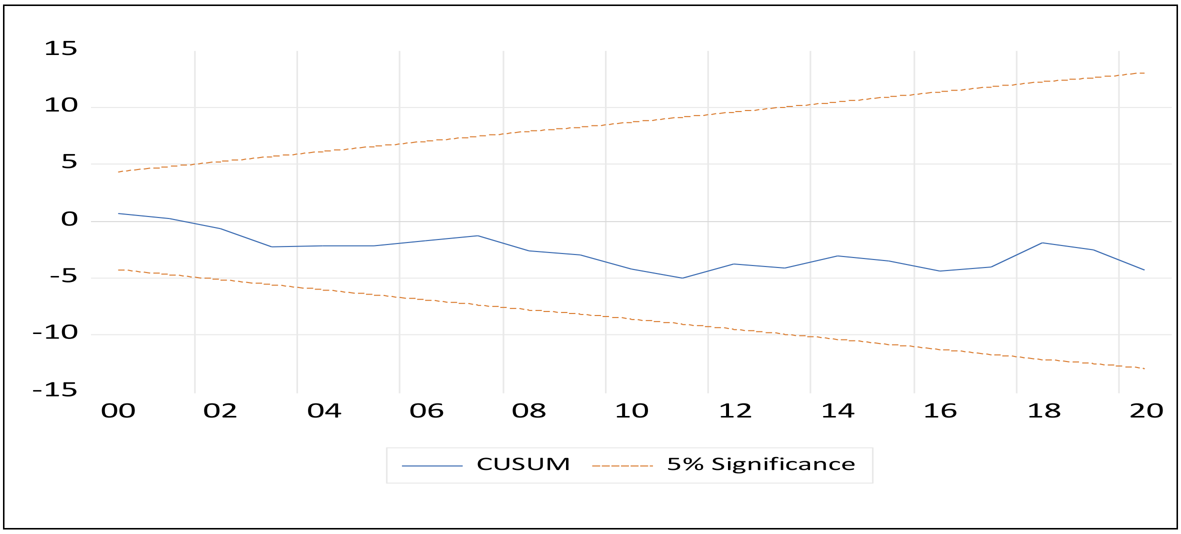
***Figure 1: Results of the Normality Test***




*Source: (Researchers' own calculation)*

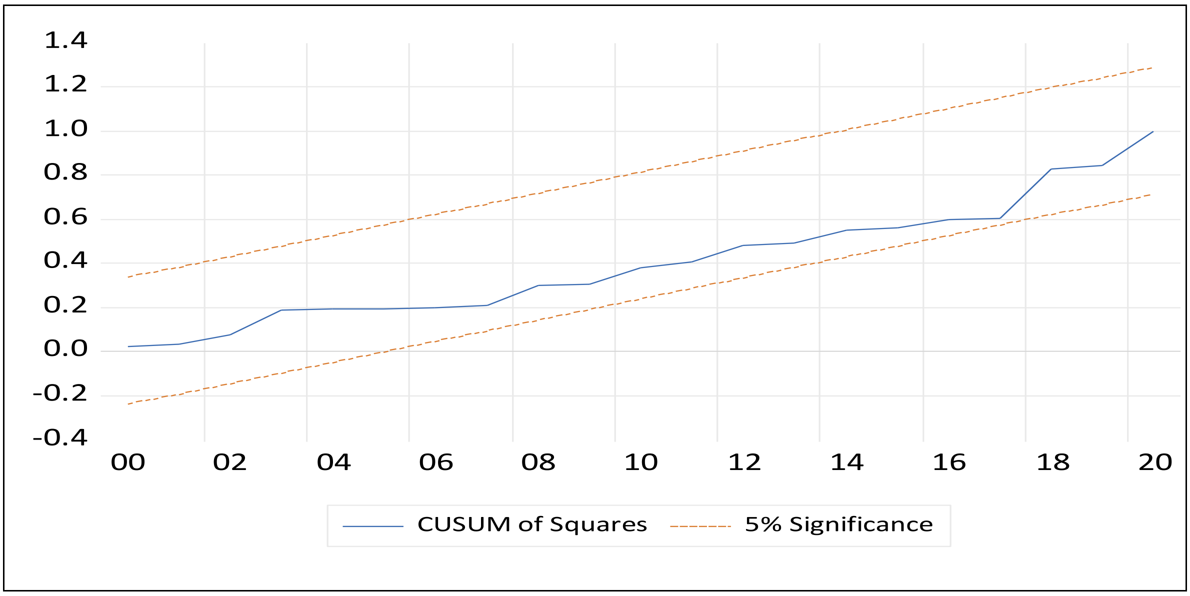
The findings of the Jarque-Bera test (Figure 1) indicate that the distribution is normally distributed because the *p*-value (0.66) is higher than 0.05.

***Figure 2: Results of the Stability Test (CUSUM Test)***




*Source:(Researchers' own calculation)*

***Figure 3: Results of the Stability Test (CUSUMSQ Test)***




*Source: (Researchers' own calculation)*

In Figures 2 and 3, the blue lines on both graphs remain inside the red lines according to the outcomes of the CUSUM and CUSUMSQ tests, which indicate that the model is constant.

## Conclusion

One of the pervasive threats that the world has been experiencing is climate change. Ensuring environmental sustainability and achieving the goal of zero $CO_2$ releases are paramount at present. However, it is observed that the energy requirements of various nations are mostly driven by non-renewable energy resources, which cause severe environmental damage and adverse effects on public health. The proper use of renewable energy, which does not pollute the environment, could repair this catastrophic damage that non-renewable energy has caused on a global scale. Like other developing economies, in India, there is a growing demand for energy to accelerate its economic activity. Despite most Indians being compelled to breathe toxic air, a notable portion of India's energy requirement is fulfilled by conventional energy sources, which deteriorates environmental quality. But in recent years, the Indian government has put stress on developing renewable energy infrastructure to make available clean energy for its citizens and promote environmental sustainability. In this regard, the present study anticipates investigating the contribution of renewable energy to ensuring environmental sustainability in India using the ARDL model. The results of this study reveal that there is a long-run as well as short-run negative association between renewable energy and $CO_2$ releases in India. The results of the Granger causality test also confirm the presence of an unidirectional relationship between renewable energy and $CO_2$ releases. This means that using renewable energy would help India achieve environmental sustainability by reducing $CO_2$ releases. These results also show favorable outcomes of different India's various renewable energy and energy transition-related initiatives. Furthermore, India placed fifth and scored high marks in the GHG emissions and renewable energy categories of the Climate Change Performance Index, 2023. However, a positive relationship is noted between technological innovation and $CO_2$ releases. This may imply that innovation in technology in India is unable to act as an instrument to bring about environmental sustainability.

### Recommendation

On the basis of the findings of the study, it is recommended that the Government should provide adequate impetus and support towards adopting the usage of renewable energies where necessary financial support along with private collaborations can be made. Moreover, technological exchanges with the host countries can also lead to a sustainable environment. Likewise, financial incentives accelerate research and development in the context of green energies.

### Policy Implications

The present study has several policy implications. First, investors can make major decisions in the context of renewable energy investments. Moreover, the government can make several collaborations with host countries for the import and export of technologies. The government can also provide the support that is necessary for technological inventions and innovations. The generation of awareness among citizens about the usage of renewable energies as an alternative is also an added benefit. Continuous monitoring can lead to greater control imposed on carbon emissions to reduce carbon emissions. There are several limitations to this study, including the possibility of including other country-specific factors in the model, such as trade openness, FDI, and economic development. This study might take into account other econometric tools and additional environmental sustainability indices, such as greenhouse gas emissions.

### Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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