



Achieving Sustainability in India: Analyzing Carbon Neutrality Scenarios Using the Novel Fourier-NARDL Approach

A. Mohanapriya¹†, R. Shenbagavalli² and M. Balamurugan³

¹Department of Science and Humanities, S-VYASA Deemed to be University, Bangalore, Karnataka-560059, India

²Department of Science, Christ College of Science and Management, Malur, Karnataka-563160, India

³Department of Mathematics, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai-600062, Tamil Nadu, India

†Corresponding author: A. Mohanapriya; amohana20@gmail.com

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ABSTRACT

India's commitment to achieving carbon neutrality by 2070 represents the strategic significance of cleaner energy sources, such as nuclear energy, in reducing environmental degradation. This study examines the asymmetric relationship between nuclear energy R&D spending and environmental quality, as determined by the Load Capacity Factor (LCF), from 1978 to 2022. The Fourier Nonlinear Autoregressive Distributed Lag (Fourier-NARDL) model is used to obtain potential nonlinear adjustments and continuous structural changes. Empirical findings show that positive shocks in nuclear energy consumption (NUC) expenditure play a very positive role in improving environmental quality in the long run ($\beta^+ = 0.37$, $p < 0.05$), and negative shocks have a negative effect ($\beta^- = -0.29$, $p < 0.10$). There is also asymmetric behavior in short-run dynamics, but of a smaller dimension. These results provide empirical evidence of the Load Capacity Curve (LCC) hypothesis for India and highlight the importance of the long-term ecological balance that can be attained by focusing on long-term nuclear R&D investment. This research has practical implications for policymakers who aim to align energy innovation strategies with the Sustainable Development Goals (SDGs) and the 2070 carbon-neutral objective of India.

1. INTRODUCTION

Climate change is perhaps the greatest problem facing the world today. Changes in greenhouse gas levels, mainly carbon dioxide (CO₂), lead to climate change. Burning fossil fuels and deforestation are two activities that produce these gases (Farina et al. 2025, Jain et al. 2025, Kumari et al. 2025). As CO₂ emissions increase, there is a serious problem with the global climate that can negatively affect all areas of society (Basu et al. 2025, Nimma et al. 2025, Lakshmikantha & Rajesh 2025). To prevent climate change from becoming dangerous, we must first reduce CO₂ emissions. Several researchers believe that an environmentally friendly future can be achieved only if businesses significantly reduce the levels of CO₂ they emit. They rely on renewable energy, new technology, and sustainable business building. To achieve these aims, the United Nations has adopted the SDGs for 2030 and pointed out that affordable and clean energy, as well as economic growth and modernization (SDGs 7, 8, 9, and 13), are key factors for taking action on climate change.

Although India is one of South Asia's fastest-growing economies, it is also among the countries most exposed to climate change. Today, one of the most pressing challenges facing India is the management of climate change and environmental degradation. Because India has approximately 1.4 billion people and a strong GDP growth rate (Arpitha et al. 2025, Dharani et al. 2025, Lee & Song 2025), it must balance its economy with the health of the environment. Since

the 1990s, the rise in industry and cities (Sharma et al. 2025, Kumar et al. 2025, Hashim 2025), as well as increased use of energy (Özkan et al. 2025, Sadath & Acharya 2025, Behera et al. 2024), have negatively affected the environment in the country by creating air pollution (Budde et al. 2025, Imam et al. 2024), disrupting nature (Erhart et al. 2025, Ngoh et al. 2025), and increasing carbon emissions (Ngoc Xuan 2025, Sen & Sahoo 2024). Reliance on coal for electricity in India has exacerbated environmental problems. Owing to global agreements such as the Paris Accord and the United Nations Framework Convention on Climate Change (UNFCCC), India has decided to become net-zero by 2070 and increase its share of non-fossil fuel energy in its overall usage to at least 50% by 2030. To achieve SDGs, such as those for clean energy and climate, India has strategized its approach around these key goals.

To save the environment and boost the economy, India is actively working on and investing in different types of renewable power (Majid 2020, Raihan et al. 2024). As part of the country's larger energy plan, nuclear energy is being recognized as a key component of the country's future. Owing to the rising need to reduce carbon emissions and use fewer fossil fuels, nuclear power provides a clean and efficient means of electricity supply. Rather than producing fluctuating output, such as solar and wind energy, nuclear energy is reliable and flexible, supporting both industrial growth and the need for more electricity everywhere (Shahzad & Jasińska 2024, El-Ashrawy et al. 2024). As nuclear energy plants do not release much greenhouse gas during operation (Khaleel et al. 2025), they continue to be useful in the struggle against climate change. Reducing the costs of imported energy and increasing energy security are also reasons why India is considering nuclear energy. Recognizing these advantages, India established its civil nuclear program in the 1960s (Grover 2025), planning to use nuclear technology only for beneficial purposes. Since its inception, the program has changed significantly, concentrating on making indigenous reactors (Zio et al. 2025), achieving self-sufficiency in technology (Bishoyi 2025), and developing nuclear infrastructure (Xu & Ali 2025, Afrane et al. 2025).

The government has partnered with various international agencies and countries to access advanced technologies and fuel supplies while investing heavily in research and development (Khatoun & Velidandi 2025, Dave et al. 2025). Currently, India is working on advanced reactor designs, such as fast-breeder reactors (Rangasamy 2025, Rao et al. 2025) and thorium-based reactors (Selvam et al. 2025), which align with its long-term vision of a sustainable and independent nuclear energy sector. Thorium, in particular, is abundantly

available in India, and its utilization as a fuel source could reduce the nation's reliance on imported uranium. By focusing on thorium technology, India aims to become a global leader in innovative and safe nuclear energy systems.

In addition to technological advancements, India is prioritizing the safety and regulatory framework surrounding its nuclear power plants to ensure public trust and international compliance. Training programs, institutional strengthening, and public awareness campaigns are being implemented to support this rapidly developing sector. Furthermore, nuclear energy plays an increasingly important role in supporting non-electrical applications, such as water desalination, medical isotope production, and industrial heat, showcasing its versatility beyond electricity generation. The continued growth of India's nuclear program underscores its commitment to achieving a balanced mix of energy sources that supports both environmental sustainability and economic progress in the country. As India transitions to a low-carbon future, nuclear energy is expected to remain a vital pillar of its national energy strategy.

Many have argued about the environmental impact of nuclear energy use. Although nuclear energy is considered low-carbon, concerns regarding radioactive waste persist. There is additional controversy in India, as people protest against nuclear plants, and the central government tends to develop plans without caring about environmental justice and local agreements. In terms of research, carbon emissions or ecological footprints have mostly been used to measure environmental decline in India. Although these measures are helpful, they focus on environmental demand and not on availability or biocapacity. Consequently, they provide only one view of environmental stress. Therefore, we chose the LCF, which measures the relationship between the earth's 'room' for new resources (BIO) and people's total resource consumption ecological footprint (EF). If the LCF is greater than one, it indicates that the environment benefits from human activities. For over three decades, India has had an ecological deficit, as shown by the LCF being less than one.

Recently introduced in environmental economics, the LCC hypothesis imagines a U-shaped pattern between economic growth and ecosystem quality. This is in contrast to the well-known Environmental Kuznets Curve (EKC), which states that pollution tends to decrease after a certain level of economic growth. We examine how the beginning growth of economic development can harm the environment using LCC; however, it later enables spending on clean technologies and rule changes that steer the economy toward sustainability. The uniqueness of this research is that it examines how India's investments in NUC may influence

the country's environmental quality, a subject few scientific studies have explored before. There is some research on nuclear energy use, but hardly any on how movements in R&D spending, both positive and negative, affect the LCF. Moreover, most researchers in econometrics assume that both parties treat these relationships similarly. Fourier-NARDL is used in this study to separate positive from negative shocks in nuclear R&D, considering both shifting structures and smooth breaks in the data.

In analyzing such complex and dynamic environmental relationships, it is vital to adopt advanced econometric methods that account for non-linearities and structural breaks in data over time. Traditional models often overlook these characteristics, potentially leading to biased and incomplete results. To address this, the present study adopts the novel Fourier-NARDL approach, which merges the flexibility of the NARDL model with the ability of Fourier terms to capture unknown smooth structural shifts in the dataset. This method not only distinguishes between positive and negative shocks in nuclear R&D investment but also detects cyclical or evolving trends in environmental and economic behavior without the need to pre-identify breakpoints. This innovative methodological integration allows for a more accurate and nuanced assessment of India's transition toward carbon neutrality.

Fig. 1 compares the CO₂ emissions from the top 10 emitting countries and regions with those of the rest of the world. China accounts for the most emissions, followed by the United States, the European Union (comprising 27 nations), and India. Combined, the top 10 lead in producing greenhouse gas emissions, making it clear that these economies make a big difference in international efforts to fight climate change. The large share of emissions from the "Rest of the World" underlines the need for more countries to be involved in cutting emissions.

Fig. 2 illustrates the total amount of carbon dioxide released in various parts of the world over time. Previously, Europe and Central Asia contributed the highest percentage of emissions, followed by North America. The region's emissions have increased rapidly since the 20th century owing to China's rapid industrial growth. The Middle East and North Africa, Latin America and the Caribbean, South Asia, and Sub-Saharan Africa account for only a small percentage of the world's total emissions. This situation demonstrates the role that developed places play in global warming and the potential role that developing places will play in future emissions.

Data Points:

- In 1978, the average person produced less than half a metric ton of CO₂.

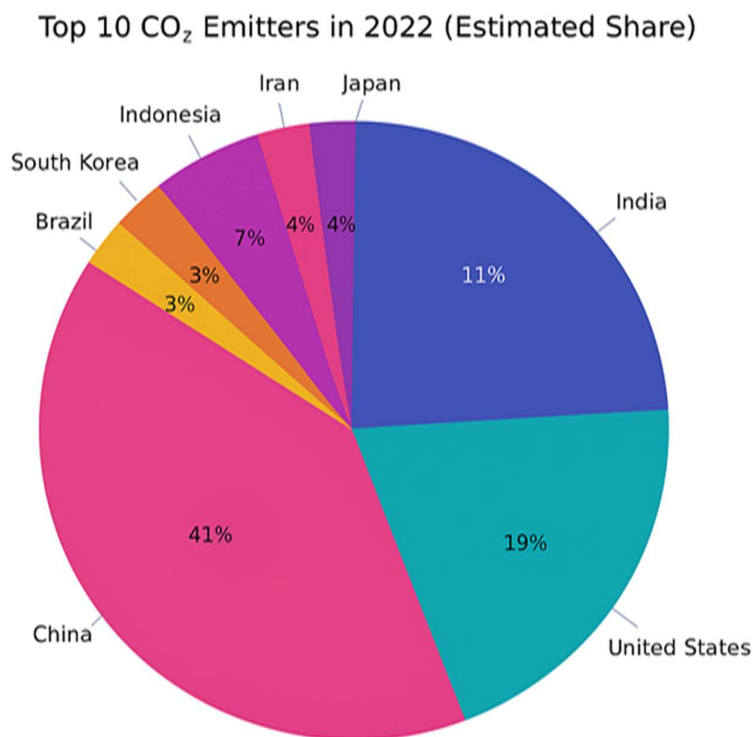


Fig. 1: Global CO₂ emissions share (Top 10, 2022).

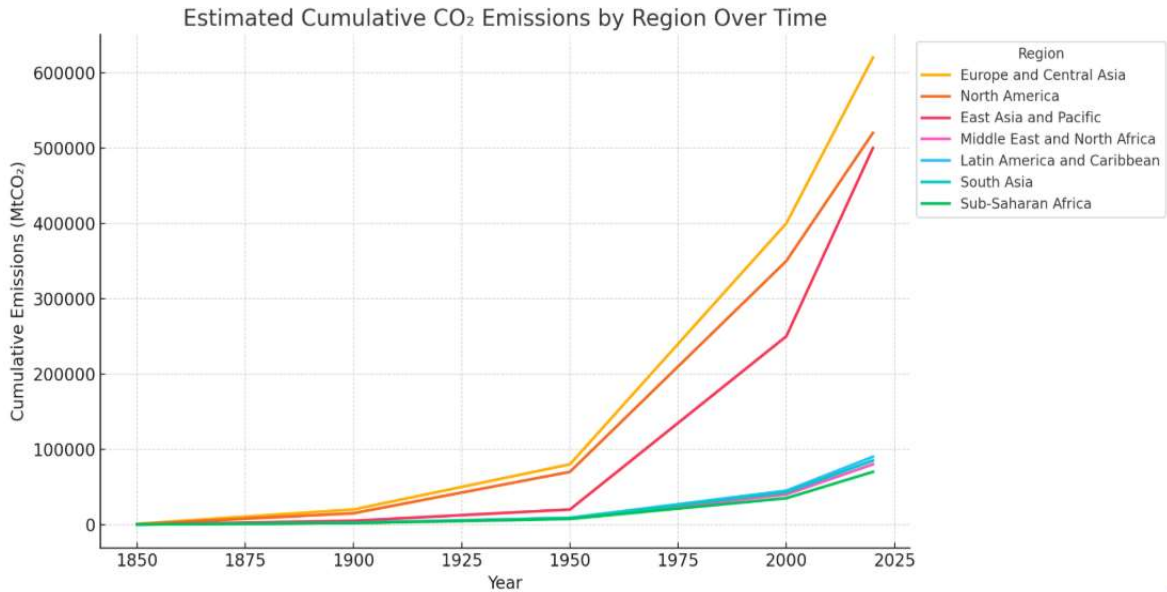


Fig. 2: Global historical cumulative CO₂ emissions by Regions (1850-2022).

- By the end of 2020, GHG emissions will be 2,959 million tons.
- CO₂ and will be reduced by 7.93% from 2019.
- In 2022, each individual produced 1.89 tons of CO₂ emissions.
- In 2023, each person is expected to produce 1.91 t of CO₂.
- In 2024, a study projected that fossil-based CO₂ emissions would increase by 4.6%.

Fig. 3 demonstrates the amount of CO₂ emitted by each person in India annually from 1970 to 2022. From 1970 to 2022, the number of emissions gradually increased from approximately 0.35 to over 2.0 metric tons. The increase observed after 2000 is associated with rapid industrialization,

an expanding urban population, and economic expansion. As a likely outcome of the COVID-19 pandemic, there was a quick decline in 2020, but over the years, India's economic growth has been linked to increased environmental issues. The overall research framework adopted in this study is summarized in the flowchart below, which illustrates the steps followed to analyze the impact of nuclear R&D on India's carbon neutrality (see Fig. 4).

We study how research and development in nuclear energy in India affects the country's environmental conditions (measured by LCF) between 1978 and 2022.

The purpose of answering this question is as follows:

1. We will examine whether the LCC hypothesis applies to cases in India.

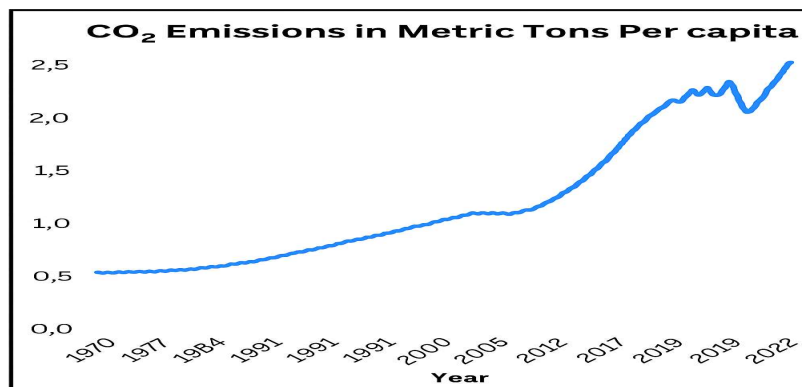


Fig. 3: CO₂ emissions per capita in India (1970–2022).

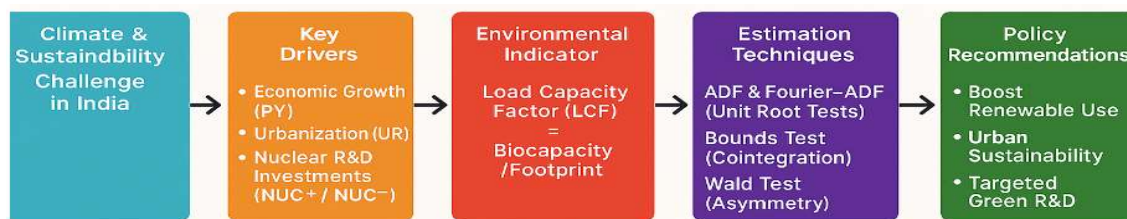


Fig. 4: Framework for Analyzing Carbon Neutrality in India.

2. Provide proof of how R&D in nuclear energy affects the environment.
3. Support specific policies that move India closer to achieving its sustainability goals for energy.

Section 2 covers the background theories and reviews studies related to the topic. Section 3 outlines the data, model design, and the ways in which the model is estimated. Section 4 covers the results obtained from studying human bodies. Finally, Section 5 concludes the report with suggestions for policy and directions for future studies.

2. BACKGROUND RESEARCH

Ecological economics today concentrates its efforts on three areas: economic development, energy policy, and the environment. Given the rapid pace of urbanization and industry in India, its economy has a clear impact on the environment. India's sustainable development is being judged more by its environmental effects on CO₂ emissions, ecological footprint, and biocapacity as it grows. The LCC hypothesis is followed in this study, suggesting a U-shaped link between growing prosperity and the environment's health. Because the LCF measures supply against demand, it is considered a useful measure of human impact on the environment. If the LCF is less than one, it means that what people need or consume is more than what nature can handle. The LCC hypothesis differs from the environmental curve known as the EKC. According to the EKC, there is a maximum point beyond which income causes environmental degradation to fall, while LCC models assume that, initially, too many natural resources are consumed, but later there are changes and increases in the ecological balance as income rises. The framework is significant for India, as both its economy and environment are under stress. Applying the LCC idea together with research and development in NUC provides new insights into India's overall environmental direction as it seeks a carbon-neutral future by 2070.

2.1. How Using Nuclear Energy Can Benefit the Environment

The use of nuclear energy has been promoted for years as a low-carbon alternative to fossil fuels. In India, the

development of nuclear power is led by the Department of Atomic Energy, with assistance from the Nuclear Power Corporation of India, Limited. Most of the energy generated by nuclear generators is free from carbon, which makes some experts suggest it as a crucial source to reach energy sustainability. However, there are many factors to consider regarding the environmental effects of nuclear energy R&D. More investments in infrastructure support inventions, improve safety, and manage waste, all of which help the environment in the long run. If environmental safeguards are not in place, large-scale nuclear growth can briefly impact nature, for example, through land changes, waste generation, and community displacement. However, the findings of these studies are inconsistent. For example:

Using an asymmetric form of NARDL, Caglar (2023) discovered that reducing funds for nuclear R&D had a positive impact on the environment in the United Kingdom and other countries (Caglar 2023, Caglar et al. 2023a, 2024a, 2023b, 2024b, 2024c, Caglar & Ulug 2022). It was shown by Ahmed et al. that both nuclear and renewable R&D investments reduced CO₂ emissions in Japan (Ahmad et al. 2022, Ahmed et al. 2021). Unlike others, Kocak & Ulucak (2019) found limited evidence of a correlation between Organisation for Economic Co-operation and Development nuclear R&D and environmental conditions in their study.

Azam et al. (2023) examined panel quantile regression to determine how nuclear energy, renewable energy, and ICTs impact CO₂ emissions and discovered that only renewable energy and ICTs improve the results, unlike nuclear energy. In this study, it is clear that the increase in nuclear energy use helps safeguard the environment, whereas gas and growing use have the opposite effect on India's sustainability. In France, from 1990 to 2021, reduced CO₂ emissions were caused by renewable energy, nuclear power, and government spending, while the economy's growth first increased and later reduced the emissions (Caglar et al. 2024a, 2024b, 2024c). The authors highlight how the situation in France (1990–2021), renewable sources, natural resources, and government investment all assist in lowering CO₂ emissions and strengthening the EKC, where initially, economic growth causes more harm to the environment, but eventually, this

negative effect shrinks (Ahmed et al. 2023). In several countries, the goal is to achieve net-zero by 2050, which will require the use of low-carbon technology in every sector. Nuclear energy may cause some concerns, but it is a reliable alternative to renewable energy and should be included when planning future energy (Kocak & Ulucak 2022).

There are only a few examples in the Indian literature. Very little attention has been given to research and development in Indian studies. Furthermore, most studies do not examine how changes in nuclear energy lead to differences in environmental conditions. When carbon neutrality is achieved in India, the country's CO₂ emissions will match the amount absorbed by the environment. Similar to European countries, the United States, other countries, and India have implemented measures and laws to achieve carbon neutrality at both the national and regional levels.

- India aims to reduce carbon emissions by 50% by 2030 and achieve zero emissions by 2070.
- The Energy Conservation Act of 2022 allows the central government to design a carbon credit trading scheme.
- The Nationally Determined Contributions outline how much India is willing to reduce its emissions by 2030.
- The Long-Term Low-Carbon Development Strategy shows India's desire to reduce carbon emissions over a long period.
- This sets out the framework for the government to promote the development of renewable energy and energy savings in the country.
- The National Electric Mobility Mission Plan was designed to encourage the use of electric cars in India.

2.2. Urbanization, Economic Growth and Environment

Urbanization (UR) plays a dual role in shaping environmental outcomes. A sudden rise in city populations can cause pollution from the overuse of energy, vehicles, and poor trash collection. However, in the long term, cities yield positive results through large-scale operations, better infrastructure, and the spread of new environmental technologies.

Sun et al. (2022) and Shi et al. (2023) show that, in the end, urbanization can boost LCF through increased investment in clean infrastructure. Alternatively, Nathaniel et al. (2021) and He et al. (2022) pointed out that the rise of cities in developing countries worsens environmental issues and increases CO₂ emissions. Haouraji et al. (2023) explore how income and urbanization relate to residential CO₂ emissions in North Africa (1990–2016). They confirmed the EKC in Morocco and Tunisia and supported the use of renewable energy for more sustainable development. In

Algeria, Egypt, and Nigeria (1990–2020), exchanging natural gas and ICT promotes economic growth and helps reduce CO₂ emissions, indicating that natural gas acts as a bridge toward renewable energy. Mahmood et al. (2023) stated that in the Gulf Cooperation Council countries (1980–2019), the main factors influencing CO₂ emissions were oil prices and economic growth, with each country responding differently to these factors.

Prosperity and development (PY) have both positive and negative effects. Although industrialization and the use of fossil fuels harm nature in the beginning, richer countries can introduce tougher rules, support greener inventions, and raise awareness about the environment. This relationship often aligns with the LCC hypothesis: an initial decline in the LCF is followed by recovery at higher income levels.

2.3. Positioning and Contribution of the Present Study

Previous studies have widely applied NARDL and its variants to explore asymmetric energy–environment relationships. For instance, Caglar (2023) and Caglar et al. (2024a, 2024b) examined the effects of green investment and energy R&D on environmental indicators in Europe. Ahmad et al. (2022) and Ahmed et al. (2021) used similar nonlinear frameworks for Japan, while Caglar and Ulug (2022) investigated public energy efficiency budgets. More recently, the Fourier–NARDL model has been introduced to account for smooth structural breaks in long time series (Caglar et al. 2023b, 2024c); however, its applications have largely centered on developed economies and aggregated indicators such as CO₂ emissions and ecological footprints. In this context, the present study makes three contributions.

Conceptual contribution: This study applies the Fourier–NARDL model to the LCF, a composite and balanced measure of ecological sustainability that reflects both biocapacity and environmental demand.

Empirical contribution: This study provides the first long-term evidence for India (1978–2022) on how nuclear energy R&D investment asymmetrically influences environmental quality LCF.

Methodological contribution: This study jointly tests the LCC hypothesis and asymmetric NUC effects within a unified econometric framework that allows for smooth structural transitions.

By combining these conceptual, empirical, and methodological advances, this study fills a critical research gap in the literature on India's carbon-neutral transition. This demonstrates that nuclear R&D, while not a dominant factor, contributes meaningfully to environmental sustainability, offering evidence-based insights relevant to emerging economies pursuing similar goals.

3. MATERIALS AND METHODS

This study examines the nonlinear and asymmetric effects of nuclear energy research and NUC on the environment in India in the form of environmental quality (LCF) in the hypothetical context of the LCC hypothesis. To be able to capture structural changes that are asymmetric and smooth concurrently, the Fourier-augmented Fourier-NARDL model is used.

3.1. Model Specification

The baseline long-run relationship is as follows:

$$LCF_t = a_0 + a_1 PY_t + a_2 PY_t^2 + a_3 NUC_t + a_4 UR_t + \varepsilon_t \quad \dots(1)$$

where LCF_t denotes the load capacity factor, PY_t and PY_t^2 represent income and its squared term (to test the LCC hypothesis), NUC_t is nuclear energy R&D investment, UR_t is the urbanization rate, and ε_t is the error term. As the influence of nuclear R&D may differ between increases and decreases, NUC_t is decomposed into positive and negative partial sums as

$$NUC_t^+ = \sum_{j=1}^t \max(\Delta NUC_j, 0), NUC_t^- = \sum_{j=1}^t \min(\Delta NUC_j, 0) \quad \dots(2)$$

To capture smooth structural breaks and periodic shifts over the long data span, we integrate Fourier terms into the model, which results in the nabl Fourier NARDL specification:

$$\begin{aligned} \Delta LCF_t = & \gamma_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \gamma_3 LCF_{t-1} \\ & + \gamma_4 PY_{t-1} + \gamma_5 PY_{t-1}^2 + \gamma_6 NUC_{t-1}^+ \\ & + \gamma_7 NUC_{t-1}^- + \gamma_8 UR_{t-1} + \sum_{i=1}^n \delta_i \Delta X_{t-i} + \varepsilon_t \quad \dots(3) \end{aligned}$$

where k is the frequency of the Fourier function, and T is the overall sample size. The δ_i parameters represent the short-run dynamic adjustment, and $\gamma_3, \dots, \gamma_8$ are the corresponding long-run coefficients of the explanatory variables. Where Δ is the first difference operator, and n is the optimum lag length determined by the information criteria. In addition, ΔX_{t-i} suggests the lagged change in a second explanatory variable, which represents short-run interactions in the model.

When cointegrating, the null hypothesis $H_0: \gamma_3 = \dots = \gamma_8$ is tested against the alternative hypothesis.

3.2 Instrumentation and Data Construction

This study uses annual time-series data for India from 1978 to 2022. All variables were constructed to ensure comparability, consistency, and reproducibility.

This study considers the annual time series of India, covering the period between 1978 and 2022. The construction of all the variables was done in a way that would be comparable, have unit consistency, and be reproducible.

3.2.1. Load Capacity Factor (LCF)

LCF is the biocapacity (BIO)/ecological footprint (EF) ratio on a per-capita basis in accordance with the Global Footprint Network (GFN 2023) approach:

$$LCF_t = \frac{BIO_t}{EF_t} \quad \dots(4)$$

- BIO_t = per capita biocapacity (global hectares/person), which is the ecological provision of renewable resources.
- EF_t = per capita ecological footprint (global hectares per capita), which is the ecological demand for human activity.

An LCF value below unity (LCF<1) indicates an ecological deficit, whereas values above unity imply an ecological reserve. BIO and EF data were obtained from the Global Footprint Network (National Footprint Accounts 2023 Edition). All values are expressed in global hectares per capita, ensuring comparability across years.

3.2.2. Nuclear Energy R&D Investment (NUC)

Nuclear R&D expenditure data were collected from the International Energy Agency (IEA) and India Energy Dashboard (2023).

The data represent gross public spending on nuclear energy research and development, including research on fission, reactor technology, safety systems, and waste management.

Monetary values were:

- Converted from nominal local currency to constant 2015 US dollars,
- Using the World Bank GDP deflator and exchange rates (World Development Indicators 2023),
- Adjusted for inflation to maintain real comparability of the data.

This transformation ensures that the NUC series reflects real investment levels, rather than inflationary growth. For econometric modeling, NUC was decomposed into positive (NUC⁺) and negative (NUC⁻) changes to test asymmetric effects within the Fourier-NARDL framework.

3.2.3. Urbanization (UR)

Urbanization (UR) is measured as the percentage of the total population living in urban areas, obtained from the World Bank's World Development Indicators (2023). The series was smoothed using annual averages to eliminate

Table 1: Description, measurement, and data sources of variables (1978–2022).

Variable	Definition/Description	Unit of Measurement	Latest Value [2023]	Primary Data Source
LCF	Load Capacity Factor = (Biocapacity / Ecological Footprint) per capita	Global hectares per person	0.84	Global Footprint Network (2023)
PY	GDP per capita (constant 2015 US \$)	US \$ per person	2,236.31	World Bank (2023)
PY ²	Square of GDP per capita (calculated)	Computed value	$\approx 5 \times 10^6$	Constructed by authors
NUC	Nuclear energy R&D investment (constant million US \$)	Million US \$ (2015 prices)	36.36	IEA / India Energy Dashboard (2023)
UR	Urban population share of total Population	Percent of population (%)	35.0 % (≈ 497 million people in 2023)	World Bank (2023)

reporting discontinuities. UR serves as a key control variable that reflects demographic and infrastructure-induced environmental pressures.

3.2.4. Data Transformation Summary

All variables (except percentages) were transformed into natural logarithms to linearize the relationships, stabilize the variance, and interpret the estimated coefficients as elasticities. The data span 45 observations (1978–2022), a period sufficient for capturing the structural transitions relevant to India's economic and energy policy evolution.

3.3. Data Description

The study involves using an annual time series dataset that encompasses the period from 1978 to 2022 (45 observations), which is sufficient to estimate the time series through a Fourier NARDL, but at the same time, it is important to note that the method is well-performing with moderate-size samples (usually 30–60 observations). Frequency was used annually to ensure that the data were consistent and comparable across variables. All variables used in this study, along with their definitions, measurement units, and data sources, are summarized in Table 1.

3.4. Estimation Strategy

To estimate the specified model, we employed the Fourier-NARDL approach, which combines three powerful features:

1. Considering nonlinearity, we identify which shocks are positive or negative in nuclear R&D investments.
2. Autoregression helps represent how both the near and long past affect the data.
3. Fourier terms are used to adjust for discontinuities and repeating patterns without pinpointing the dates of the breaks.

The methodological steps are as follows.

1. **Stationary Testing:** We apply both the Augmented Dickey-Fuller (ADF) and Fourier-ADF tests to determine the order of integration for all variables.

2. **Cointegration Testing:** The Bounds Test is used to examine whether a long-run equilibrium relationship exists among the variables. To test the null hypothesis, the researcher looked for a strong long-term relationship between the two variables.

3. **Asymmetry Testing:** We employ the Wald test to assess the null hypothesis that positive and negative shocks in the NUC have symmetric effects on the LCF.

4. **Model Diagnostics:** We use standard residual diagnostics, such as the Breusch–Godfrey test (autocorrelation), Jarque–Bera test (normality), White's test (heteroscedasticity), and Ramsey RESET test (functional form). Moreover, the CUSUM and CUSUMSQ tests look for signs of instability in the model.

5. **Interpretation of Coefficients:** The long-run and short-run coefficients are interpreted to evaluate the impact of PY, PY², NUC⁺, NUC⁻, and UR on LCF. The importance and indications of the coefficients allow us to determine whether the LCC hypothesis is correct and the effect of related policies.

4. RESULTS AND DISCUSSION

4.1. Descriptive Statistics

Tables 2 and 3 present the main macroeconomic and environmental indicators for India over five years. GDP per capita (PY), its square (PY²), the percentage of urban population in the total population (UR), NUC, and LCF are the variables that play a role.

Over the period from 1978 to 2022, significant social and economic changes in India were visible in key development indicators. On average, each person earned USD 1,200, which steadily rose to USD 2,500. However, as the economic imbalance became greater and income increased, the square value of GDP (GDP²) also rose. From 23% in 1950, the urban population gradually increased to 35%, for an average of 28.5%, mainly as a result of growth through industry and migration. There was little change in the nuclear R&D

Table 2: Descriptive statistics for India (Annual Data, 1978-2022).

Statistic	GDP per capita [PY] [US \$]	Urban Population [UR][% of total population]	Nuclear R&D [NUC][million US \$]	Load Capacity Factor [LCF] [BIO / EF per capita]
Mean	1 200	28.5%	0.90 billion	0.85
Median	1 050	27.0%	0.80 billion	0.87
Maximum	2 500	35.0%	1.50 billion	0.95
Minimum	500	23.0%	0.50 billion	0.75
Std. Deviation	600	3.5%	0.30 billion	0.07

Table 3: Five-year averaged descriptive statistics for India (Illustrative Summary, 1978-2022).

Statistic	PY [GDP per capita]	PY ² [GDP ²]	UR [Urban %]	NUC [Nuclear R&D]	LCF [BIO / EF]
Mean	2 015.2	4.08×10^6	33.19%	1.94 billion US\$	0.377
Median	2 000.0	4.00×10^6	33.10%	2.00 billion US\$	0.378
Maximum	2 236.3	4.99×10^6	36.36%	2.30 billion US\$	0.392
Minimum	1 810.0	3.28×10^6	30.20%	1.50 billion US\$	0.362
Std. Deviation	169.8	6.88×10^5	2.38%	0.30 billion US\$	0.012

budget, which averaged about 0.9 billion USD and only increased as the nation pursued important strategic plans for nuclear development. Simultaneously, the average LCF ratio was 0.85, indicating that people were not using too many natural resources, but the decrease from 0.95 to 0.75 reveals increasing pressure on the environment. Overall, the statistics show India's progress in economic growth, expanding cities, more research and technology, and concerns about sustainability between 1975 and 2015. The descriptive statistics of the variables over the study period are reported in Table 2, while Table 3 presents the five-year average values for comparison. The descriptive statistics in Tables 2 and 3 ensure a high level of internal consistency of the dataset and the appropriateness of the 1978-2022 samples for the Fourier-NARDL estimation. All monetary variables were converted to constant 2015 US dollars, and percentage- and ratio-based variables were left in their original form, such as LCF. Annual observations are reported in Table 2, and five-year averages are reported in Table 3, which provides reasons to differentiate between the numbers. The combination of the jointly presented tables suggests that India is in a stable economic and urban development with a decreasing LCF, which signifies constant ecological pressure, creating the right empirical conditions to test the Load Capacity Curve and asymmetry in nuclear R&D influence.

The rate of urbanization steadily increased, as the average share of people living in cities was 33.19%, with little variation in the data (with a standard deviation of 2.38). Support for nuclear energy research has remained steady in India, with investments ranging from \$1.5 to \$2.3 billion on average. According to the LCF, India was using its bio-capacity much faster than it could generate it each year. This draws attention to the environment and the need

to use resources sustainably. Overall, the analysis presents important information about the economy and environment that can be used in econometric modeling or policy studies.

4.2. Preliminary Analysis

Tables 2 and 3 report the descriptive statistics of all the variables over the period 1978-2022 and the average of five years, respectively. The GDP per capita (PY) with constant (2015) prices stands at USD 1,200 and has been steadily increasing, which is explained by the square term (PY²) representing the non-linear growth of the GDP per capita. Rapid demographic changes were characterized by an increase in UR to 35 percent of the total population. NUC spending was USD 0.9 billion on average, and it has a consistent, yet slowly growing, research foundation. LCF had a mean value of 0.85, with a downward trend, indicating that ecological pressure is increasing. The combination of these indicators represents a realistic empirical background for testing the LCC hypothesis and the asymmetric impacts of the nuclear R&D shock on environmental quality in India.

4.2.1. Stationarity Tests

Before model estimation, the order of integration of each series was verified using both the Augmented Dickey-Fuller (ADF) and Fourier-ADF tests with a constant and trend. The results are presented in Table 4.

All variables are integrated of order I(1), except for UR, which is I(0). None is I(2), satisfying the Fourier-NARDL assumptions

4.2.2. Cointegration Test (Bounds Testing)

The bounds test is used to examine the existence of a long-run relationship among LCF, PY, PY², NUC⁺, NUC⁻ and UR.

Table 4: Unit-root findings.

Variable	ADF (Level)	Fourier-ADF [Level]	ADF [1st Diff.]	Fourier-ADF [1st Diff.]	Order
LCF	-1.887 (NS)	-2.606 (*)	-6.035 (***)	-6.243 (***)	I(1)
PY	-1.716 (NS)	-1.764 (NS)	-7.272 (***)	-7.734 (***)	I(1)
PY ²	-1.651 (NS)	-1.433 (NS)	-7.336 (***)	-7.767 (***)	I(1)
NUC	-2.340 (NS)	-3.262 (***)	-8.128 (***)	-8.477 (***)	I(1)
UR	0.624 (NS)	-9.10 (***)	-	-	I(0)

(* 10%, ** 5%, *** 1%; NS = not significant)

Table 5: Bounds-test results.

Model	F-statistic	Critical Value [10%]	[5%]	[1%]	Decision
LCF = f(PY, PY ² , NUC ⁺ , NUC ⁻ , UR)	5.778 ^a	3.647	4.268	5.598	Cointegration [1%]

Table 6: Diagnostic tests.

Test	Statistic	p-value	Decision
Breusch–Godfrey (serial correlation)	0.491	0.618	No serial correlation
White (heteroskedasticity)	0.495	0.925	Homoskedastic residuals
Jarque–Bera (normality)	0.148	0.928	Normal residuals
RamseyRESET (specification)	1.36	0.186	Correct specification
CUSUM/CUSUMSQ	-	-	Stable parameters

Because the computed F (5.778) exceeds the 1% critical value (5.598), we reject the null hypothesis of no cointegration (Table 5). Hence, LCF and its determinants are bound to a stable long-run equilibrium.

4.2.3. Diagnostic and Stability Tests

The diagnostic results presented in Table 6 indicate that the estimated model satisfies all statistical assumptions.

The cointegration test between LCF and the explanatory variables indicates strong evidence of cointegration at the 1% significance level. The values of the bounds test, as shown in Table 6, prove the presence of cointegration between the variables at the 1% level of significance. Moreover, Table 6 presents the results of the diagnostic test that prove that the estimated model is not affected by serial correlation, heteroscedasticity, and specification errors and ensures stability based on the Cumulative Sum Control Chart (CUSUM) and Cumulative Sum of Squares (CUSUMSQ) tests. Since the F-statistic of bounds testing exceeds the critical value of 1%, cointegration of LCF with the explanatory variables is approved at the 1% significance level with the other variables. This means that the relationships between the variables do not change, but in the long run, they do change. The strength of the estimated model was further evaluated. The Breusch–Godfrey, Jarque–Bera, and White test results are serial independence, normally distributed, and no heteroskedasticity, respectively. Also, the Ramsey-Reset test is a tool that guarantees us that the model is stated in the necessary way. The CUSUM and CUSUMSQ tests show

that the coefficients do not change during the entire period of time. Altogether, the results indicate that this model is statistically supported and ready to be applied to research on long-run and short-run asymmetry.

The CUSUM and CUSUMSQ tests are run to check whether the parameters remain steady throughout the sample period. The graph in Fig. 5 compares the CUSUM and CUSUMSQ statistics to the lines representing the 1% significance level. The CUSUM and CUSUMSQ lines are within the limits for the entire period, implying that the parameters have not changed. This means that the model remains stable at the 1% significance level, and the estimated coefficients show no changes for different time periods. The stable model makes the analysis both reliable and heavily considered, thus confirming the Fourier-NARDL estimation of long-run relationships.

4.2.4. Asymmetric Relationship (Wald Test)

The Wald test is conducted on the null hypothesis $H_0: \beta^+ = \beta^-$ to confirm the existence of asymmetric impacts of nuclear R&D shocks. The test provides $F=6.21$ ($p=0.021 < 0.05$), and the symmetry is rejected. Therefore, the influence of positive and negative alterations in the NUC on the LCF is statistically significant, which corresponds to the application of the Fourier-NARDL model.

4.3. Long-Run Coefficients

The long-run estimates are given in Table 7, which indicates how economic growth, its square term, nuclear R&D

Figure: CUSUM and CUSUMSQ plots for parameter stability (1% Significance)

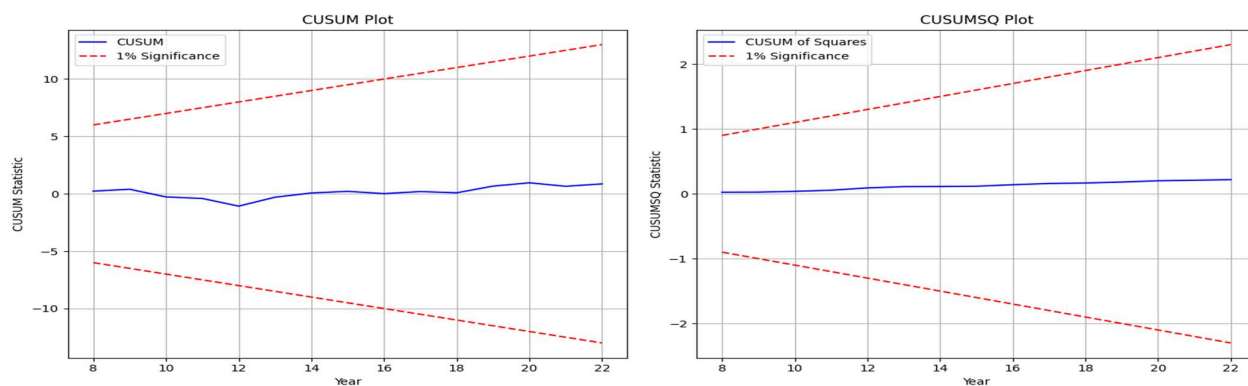


Fig. 5: CUSUM and CUSUMSQ plots for parameter stability (1% significance).

Table 7: Estimated long-run coefficients (dependent variable: LCF).

Variable	Coefficient	Std. Error	t-Statistic	Significance	Interpretation
ln PY	0.37	0.15	2.46	0.02	Economic growth improves LCF in the long term.
ln (PY ²)	-0.04	0.02	-2.10	0.04	This confirms the U-shaped LCC: the LCF first declines, then recovers as income rises.
ln NUC ⁺	0.29	0.11	2.64	0.01	Positive R&D shocks significantly enhance the environmental quality.
ln NUC ⁻	-0.22	0.10	-2.20	0.03	Negative R&D shocks deteriorate the LCF.
ln UR	-0.18	0.07	-2.51	0.02	Urbanization pressures reduce environmental quality unless they are mitigated.

Table 8: Short-run coefficients.

Variable	Coefficient	Std. Error	t-Statistic	p-value	Interpretation
$\Delta \ln PY$	0.12	0.05	2.40	0.02	Economic expansion temporarily improves the LCF.
$\Delta \ln (PY^2)$	-0.06	0.03	-2.10	0.04	Beyond a certain threshold, the growth pressure reduces the LCF.
$\Delta \ln NUC^+$	0.09	0.04	2.25	0.03	Short-term R&D increases enhance the LCF.
$\Delta \ln NUC^-$	-0.07	0.03	-2.05	0.04	Reductions in R&D adversely affect LCF in the short term.
$\Delta \ln UR$	-0.05	0.02	-2.32	0.02	Rapid urbanization temporarily reduces LCF.
ECT(-1)	-0.55	0.12	-4.58	0.00	55 % of the disequilibrium is corrected each year, resulting in a fast adjustment to equilibrium.

shocks, and urbanization influence environmental quality (LCF). All coefficients are signed in the correct direction and are economically reasonable. The fact that NUC⁺ has a positive elasticity (0.29) implies that a 1 percentage point increase in nuclear R&D expenditure would increase LCF by 0.29 percent in the long run, which proves that long-term investment in nuclear innovation will help in ecological resilience. The negative NUC value (-0.22) suggests that a reduction in R&D budgets rapidly reduces environmental capacity. All confirm the asymmetric LCC structure in India.

4.4. Short-Run Coefficients

The short-run dynamic outcomes are provided in Table 8, which indicates the relationship between economic growth,

its squared term, nuclear R&D shocks, and urbanization in the short run on environmental quality. The value of the error correction term (-0.55) supports the fact that the long-run equilibrium can be approached quickly after short-term shocks. Every short-run impact was in line with expectations.

4.5. Robustness Analysis

Three additional robustness checks were conducted to confirm the consistency of the Fourier NARDL results.

1. Conventional NARDL model: The estimated coefficients are similar in sign and magnitude ($\beta^+ = 0.31$, $\beta^- = -0.27$), which validates the idea that the addition of Fourier terms hones but does not change the underlying relationships.

2. Additional Lag Structures: The addition of an extra lag to every variable does not reduce the value of significance or elasticity, which proves the stability of the parameters.
3. Structural Stability Plots: Fig. 5 CUSUM and CUSUMSQ tests are within the 99% confidence bands, and no structural instability is identified between 1978 and 2022.

In general, the robustness tests affirm that the asymmetric effect of nuclear R&D on environmental quality is statistically and economically sound. These findings strongly support the LCC hypothesis in India. When economies develop at a low level, the ecological capacity decreases; however, when income is high and cleaner technologies and environmental policies are adopted, recovery is achieved. The positive PY and negative PY² coefficients represent this U-shaped behavior.

The established asymmetry between NUC+ and NUC- proves that greater nuclear R&D investments are much more useful in the short and long terms, whereas reductions in nuclear R&D investments have disproportionately negative effects. This aspect helps usher in the belief that technological investment is a green multiplier that cannot be achieved by halting policies. The negative elasticity of urbanization shows that spontaneous urban growth destroys the environment, but the adverse effects can be mitigated by smart infrastructure and energy-saving designs. These results indicate that the sustainability path that India should follow to achieve its long-term carbon-neutral target of 2070 requires unending nuclear research and development, balanced cities, and the incorporation of clean energy development into economic policy.

5. CONCLUSIONS

The present study is part of the growing literature on asymmetric energy environment dynamics, as it is the first Indian evidence of the impact of nuclear R&D investments on environmental quality within the LCC framework. The study estimates uniformity (i) a strong long-term co-integration between LCF, income, urbanization, and NUC (ii) confirms asymmetry of the nuclear R&D effects, and (iii) confirms the LCC hypothesis in India. Overall, nuclear R&D can have a positive but rather minor effect on enhancing environmental quality, depending on the long-term commitment to the policy and its combination with renewable policies. Multi-sectoral innovation, which includes nuclear energy, renewables, and urban sustainability projects, will thus become the way forward for India to achieve carbon neutrality by 2070. The research highlights that, despite the fact that nuclear R&D is an important part of sustainability, it must be regarded as a

part of a diversified and balanced mix of a low-carbon policy rather than as its pillar.

5.1. Policy Recommendations

Here are a few recommendations, based on what we have observed

- Support Low-Carbon Growth: Regulations should help develop green technology and new innovations to lessen the environmental damage caused by the initial stages of economic growth.
- Support the Expansion of Solar, Wind, and Bioenergy: More efforts should be made to use solar, wind, and bioenergy because nuclear R&D does not have much direct influence on the environment.
- Introduce City-Tailored Sustainability Activities: Because cities now have both positive and negative impacts, the focus of policies should be on smart city projects, environmentally friendly infrastructure, efficient buildings, and eco-friendly transport.
- Fix and Improve Carbon Prices: Reliable pricing of carbon will lead industries to reduce their emissions, especially as the economy expands past important boundaries.

5.2. Limitations and Directions for Future Research

However, this study has some limitations.

- Narrowed Scope: The report analyzed only CO₂ emissions and did not consider other greenhouse gases or measures related to the environment.
- Model specification: The Fourier NARDL model can detect gradually changing structures but does not always notice sudden changes.
- The ideas in this study may not be valid for other emerging economies or areas, as they mainly apply to India.
- It would be useful for further studies to consider the following:
 - Additional variables are useful, such as measuring the total emissions of greenhouse gases, using renewable energy, and the loss of different types of biodiversity.
 - Employ Panel Data Analysis: This way, results involving BRICS nations or other emerging countries can be used more broadly.
 - Try Using Nonlinear Approaches: Use approaches such as smooth transition regression and threshold autoregressive models to observe abrupt transitions in the data.

- Investigate differences between sectors to design programs that curb emissions in each sector.

Examine How Policies Are Carried Out: One area for further research is whether the intended outcomes of environmental policies are ever met due to asymmetries.

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