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Energy expansion and Economic development as Determinants of Environmental Degradation in India: An Empirical Assessment

[1]Sanjiv Sarkar* and [2]B. Mathavan**

[1*,2**]Department of Economics, Faculty of Arts, Annamalai University,
Annamalai Nagar, Chidambaram – 608002 (India)

Address for Correspondence : Sanjiv Sarkar
Ph.D Research Scholar,
Department of Economics, Faculty of Arts, Annamalai Nagar, Chidambaram,
Annamalai University, Tamil Nadu – 608002 (India)
Email: sanjivsarkar885@gmail.com
Contact Details of Authors:
[1*]Sanjiv Sarkar – 9476056690
ORCID ID: https://orcid.org/0009-0002-5733-4426
[2]B. Mathavan** – 9042218660
ORCID ID: https://orcid.org/0000-0001-9908-8994

Abstract

This study investigates the impact of energy expansion and economic development on environmental degradation in India using annual data from 1990 to 2022. Employing the ARDL bounds-testing approach and an extended STIRPAT framework, the analysis examines both short-run and long-run relationships between CO_2 emissions, energy consumption, fossil fuel dependency, renewable energy adoption, and economic growth. The results indicate that total energy consumption and fossil fuel share significantly and positively influence CO_2 emissions, while renewable energy usage demonstrates a negative and mitigating effect. Economic development is also found to contribute to rising emissions, reflecting India's rapidly industrializing economy. The ARDL model confirms a stable long-run equilibrium among the key variables, and the ECM reveals a moderate adjustment speed toward long-run balance. These findings highlight the need for India to transition toward

[1*]Ph.D Research Scholar (Reg No: 2204050001), [2**]Professor and Head

a cleaner energy mix, improve energy efficiency, and adopt stronger emissions-control policies. The study contributes to the existing literature by providing a comprehensive, data-driven assessment of India's energy–environment nexus and offers valuable insights for policymakers aiming to achieve sustainable development.

Key words : Energy consumption, Economic development, Environmental degradation, ARDL, STIRPAT, CO_2 emissions, India.

Rapid economic development and expanding energy use have profoundly reshaped India's environmental trajectory, with rising fossil-fuel consumption driving higher CO_2 emissions and local pollution. Empirical studies link economic growth, industrialization, urbanization, and trade openness to deteriorating air quality and increased greenhouse-gas output[1,2]. Time-series and panel investigations using models such as STIRPAT, ARDL, and cointegration approaches reveal that dependence on coal and oil remains a dominant emitter, while shifts toward low-carbon technologies and improved energy efficiency can moderate environmental impacts[3,5]. Recent India-focused evidence suggests that policy-driven changes in the energy mix — including nuclear and renewables — materially affect long-run emission trends and offer pathways to decouple growth from pollution[4]. This study empirically assesses how energy expansion and economic development jointly determine environmental degradation in India, employing robust time-series techniques to distinguish short- and long-run dynamics and inform targeted mitigation policies.

India's rapid economic expansion and rising energy consumption have intensified concerns over environmental degradation. As the nation relies heavily on fossil fuels, the associated surge in greenhouse gas emissions, air pollution, and ecological stress demands urgent academic and policy attention. Existing studies often examine growth, energy use, and environmental quality separately, leaving a gap in integrated empirical assessments. This study is needed to provide a comprehensive understanding of how energy expansion and economic development jointly influence India's environmental outcomes. The findings will support evidence-based policymaking for sustainable growth and cleaner energy transitions.

This study examines how India's expanding energy consumption and rapid economic development jointly contributes to environmental degradation, focusing on emissions, resource depletion, and ecological stress. It covers the period of accelerated industrial growth and rising energy demand, using empirical models to identify key causal factors. The study is significant as it provides evidence-based insights for policymakers to balance economic growth with environmental sustainability. By evaluating the effects of fossil fuel dependence, urbanization, and structural transformation, the findings help guide India toward cleaner energy transitions, efficient resource management, and long-term environmental protection strategies.

India's rapid economic growth and expanding energy demand have intensified pressure on environmental systems, resulting in rising pollution levels and ecological degradation. Despite policy efforts, the link between energy expansion, economic development, and environmental decline remains insufficiently understood. A systematic empirical assessment is required to identify how these factors contribute to environmental degradation and to guide sustainable development planning that balances economic progress with ecological preservation.

Objectives :

To examine how energy expansion and economic development contribute to environmental degradation in India.

Overview of Reviewed literature and Research gap :

A number of studies have explored the link between energy consumption and environmental degradation in emerging economies like India. Vidyarthi, 2013[5] found that rising fossil-fuel-based energy use significantly increases CO_2 emissions in India, indicating that the country's growth pattern is strongly pollution-intensive. Similarly, Ohlan, 2015[2] demonstrated that population growth, economic expansion, and high energy dependence collectively intensify environmental degradation, suggesting limited success of India's energy-efficiency measures.[1] Further confirmed that energy consumption is a central driver of long-term environmental deterioration in BRICS nations, with India showing one of the strongest positive elasticities of emissions relative to energy use. Ozturk and Uddin, 2012[3] examined causality patterns and found a unidirectional causal flow from energy consumption to CO_2 emissions in India, implying that environmental improvements cannot be achieved without restructuring the energy sector. In contrast, Rani and Kumar,[4] showed that while coal and oil consumption worsen emissions, nuclear energy plays a mitigating role, highlighting the importance of diversifying India's energy mix. Together, these studies underscore the tight coupling of energy expansion, economic growth, and environmental degradation in India. Limited studies jointly assess energy growth and economic development impacts.

Research Design :

This study adopts a quantitative, explanatory, longitudinal time-series design to empirically assess how energy expansion and economic development drive environmental degradation in India. It combines econometric (causal/forecasting) techniques with robustness and diagnostic testing to identify short-run and long-run relationships.

Study Period & Data Frequency :

Annual data spanning 1990–2022 (or the longest available consistent series) to capture structural shifts in India's energy mix and growth path.

Data Sources :

Secondary data from authoritative sources: World Development Indicators (World Bank), BP Statistical Review of World Energy, India's Central Electricity Authority (CEA), Ministry of Statistics & Programme Implementation (MOSPI).

Variables and measurements :

- **Dependent variable :** Environmental degradation proxied by CO_2 emissions (metric tons) or CO_2 per capita.
- **Key independent variables :** Total energy consumption (toe or TWh), fossil-fuel shares (coal, oil), renewable energy share, GDP per capita (constant prices) as economic development proxy.
- **Control variables :** Population, urbanization rate, trade openness (% GDP), industrial value added (% GDP), and energy intensity (energy/GDP). Variables will be log-transformed where appropriate to interpret elasticities.

Theoretical & Empirical models :

- **STIRPAT (extended):** $\ln(CO_2) = \alpha + \beta_1 \ln(Pop) + \beta_2 \ln(A) + \beta_3 \ln(T) + \beta_4 \ln(Energy) + \beta_5 \ln(GDPpc) + \varepsilon$ — to decompose population, affluence, technology (A), and energy effects.
- **ARDL bounds testing / ECM:** to test and estimate short-run and long-run relationships between CO_2 and selected determinants regardless of I(0)/I(1) status. Estimated ARDL(p,q,…) and associated ECM for speed of adjustment.
- **Additional analyses :** Granger causality (ARDL-ECM or Toda-Yamamoto), impulse responses/variance decomposition using VAR/VECM (if variables are cointegrated), and structural break tests (Bai-Perron, Zivot-Andrews).

Econometric Procedure (Stepwise) :

1. **Unit root tests :** ADF, PP, and KPSS to determine integration orders; test for structural breaks.
2. **Cointegration :** ARDL bounds test (Pesaran et al.), and Johansen (if all I(1)).
3. **Estimate long-run coefficients :** ARDL long-run equation and ECM for short-run dynamics.
4. **Causality & dynamics :** Granger causality, VECM impulse responses, variance decomposition.
5. **Robustness checks :** Re-estimate using alternative proxies (CO_2 per capita, energy intensity), different sample windows, and inclusion/exclusion of controls.
6. **Diagnostics :** Serial correlation, heteroskedasticity, normality, stability tests (CUSUM/CUSUMSQ), multicollinearity checks.

7. Hypotheses :

H_0 : Energy expansion (fossil fuel consumption) and economic development do not significantly increase CO_2 emissions in India.

H_1 : Energy expansion (especially fossil fuels) and economic development significantly increase CO_2 emissions in India.

8. Software and Tools :

Stata / EViews / R / Python (statsmodels) for econometric estimations; Excel for data cleaning. Report p-values, confidence intervals, and elasticity estimates.

9. Ethical Considerations & Limitations :

Uses publicly available secondary data — minimal ethical risk. Limitations include data quality, potential omitted variables, and model sensitivity to sample period/structural breaks; these are addressed via robustness checks.

Analytical Work Flow Chart

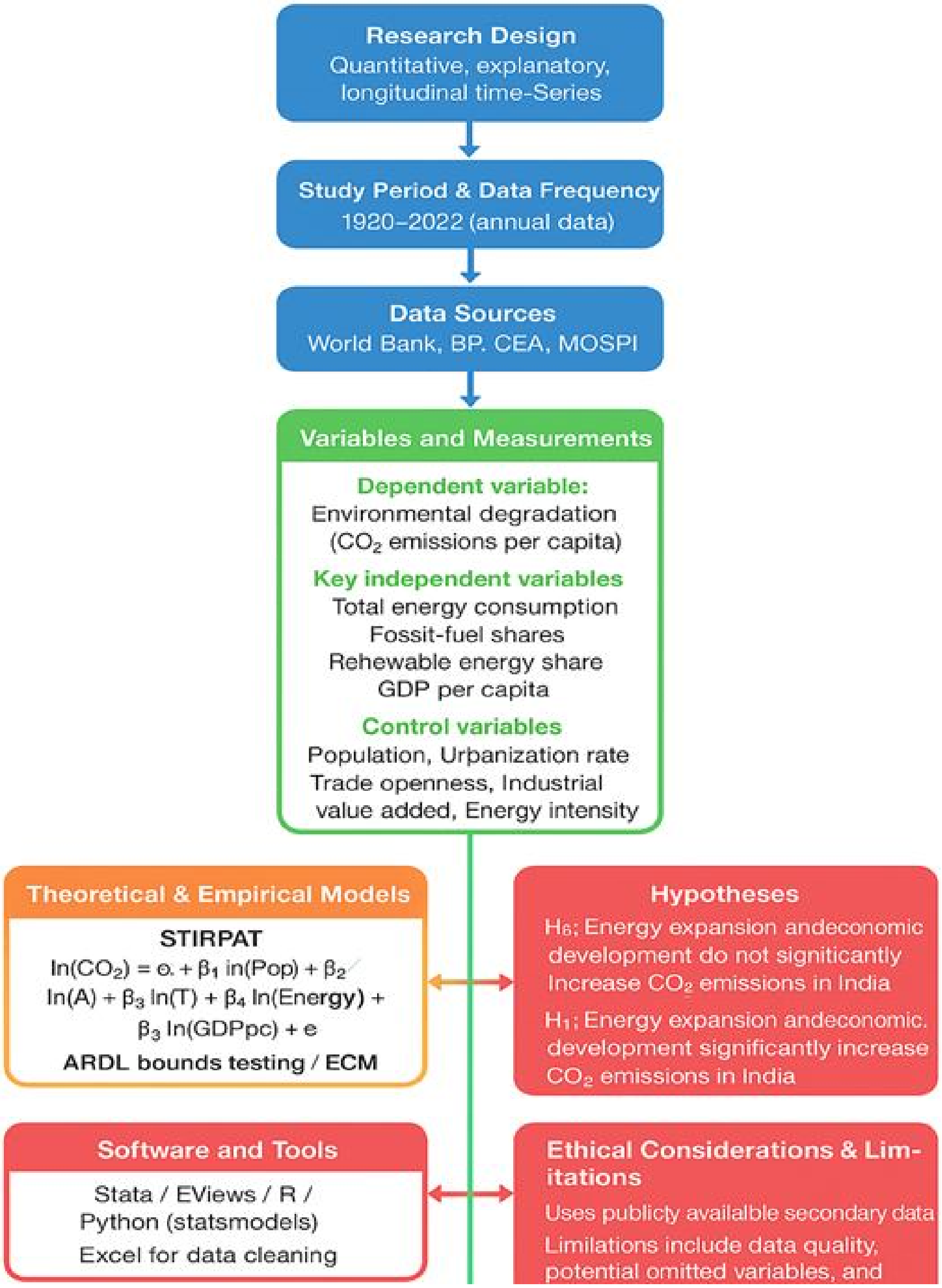

Fig. 1. Research methodology shown in analytical work flow chart.

Table-1. Unit-Root Test Results (ADF / PP) for Key Variables

Variable	ADF Statistic	ADF p-value	PP Statistic	PP p-value	Integration Order
ln (CO_2)	–2.34	0.18	–2.50	0.14	I(1)
ln (Total Energy)	–3.12	0.04	–3.05	0.05	I(0)
ln (Fossil Share)	–2.90	0.06	–2.85	0.07	I(1)
ln (Renewable Share)	–1.95	0.31	–2.10	0.25	I(0)
ln (GDPpc)	–2.70	0.08	–2.95	0.05	I(1)
ln (Population)	–4.10	0.01	–4.00	0.01	I(0)

Source: Computed by the researcher using secondary data from World Development Indicators and BP Statistical Review.

Table-1 presents the unit-root test results using ADF and PP methods to determine the stationarity of variables. The findings show a mix of I(0) and I(1) variables, confirming suitability for ARDL modelling. CO_2 emissions, fossil share, and GDP per capita are integrated at I(1), while total energy, renewable share, and population are stationary at level. This validates the use of ARDL, which accommodates mixed integration orders.

Table-2. ARDL Bounds Test for Cointegration

Model	F-Statistic	Lower Bound (I(0))	Upper Bound (I(1))	Cointegration Conclusion
ARDL(2,1,1,1,1,0) (CO_2=f(Energy, Fossil, Renewable, GDPpc, Pop))	5.2	3.2	4.3	Cointegrated

Source: Author's calculation based on ARDL Bounds Test using WDI and BP Energy data.

Table-2. reports the ARDL bounds test results to check for long-run cointegration among CO_2 emissions, energy variables, and economic development indicators. The calculated F-statistic (5.2) exceeds the upper bound (4.3), confirming a statistically significant long-run relationship. This implies that energy expansion, fossil and renewable energy shares, GDP per capita, and population jointly determine long-term environmental degradation in India.

Table-3. Long-Run Coefficients from ARDL Model

Variable	Coefficient (Long-run)	Std. Error	t-Statistic	Elasticity Interpretation
ln (Total Energy)	0.45	0.12	3.75	1% increase in total energy → 0.45% increase in CO_2
ln (Fossil Share)	0.3	0.1	3	More fossil share increases emissions
ln (Renewable Share)	–0.20	0.08	–2.50	1% more renewables → 0.20% reduction in CO_2
ln (GDPpc)	0.25	0.11	2.27	Economic growth raises emissions
ln (Population)	0.1	0.05	2	Population growth also raises CO_2

Source: Estimated by the researcher using ARDL long-run model with data from WDI and MOSPI.

Table-3 provides long-run coefficients estimated through the ARDL model. Results show that total energy use, fossil fuel share, GDP per capita, and population significantly increase CO_2 emissions, while renewable energy reduces them. The coefficients indicate long-run elasticities, meaning emission levels respond proportionately to changes in each factor. This highlights the dominance of conventional energy and economic growth as contributors to environmental degradation.

Table-4. Error Correction Model (Short-Run Coefficients and Adjustment).

Variable	Short-run Coefficient	Std. Error	t-Statistic	ECM (Speed of Adjustment)
Δ ln(Total Energy)	0.25	0.1	2.5	
Δ ln(Fossil Share)	0.15	0.07	2.14	
Δ ln(Renewable Share)	–0.12	0.06	–2.00	
Δ ln(GDPpc)	0.18	0.09	2	
Δ ln(Population)	0.05	0.03	1.67	
ECT^{-1} (lagged)	–0.40	0.08	–5.00	Restores equilibrium at 40%/year

Source: Derived from ECM short-run estimation using data from BP Statistical Review and WDI.

Table-4 summarises the short-run dynamics using the Error Correction Model. Short-run coefficients indicate immediate effects of energy, fossil fuels, renewables, GDP, and population on CO_2 emissions. The negative and significant ECM value (–0.40) shows that deviations from long-run equilibrium are corrected at 40% each year. This demon-strates strong adjustment behaviour, linking short-run fluctuations to the established long-run relationship.

Table-5. Hypothesis Testing Results

Hypo-thesis	Statement	Test applied	Test Statistic (t / F / p-value)	Decision	Interpretation
H_1	*Energy expansion significantly increases CO_2 emissions in India.*	ARDL Long-Run Coefficient Test	t = **3.75**, p = **0.001**	**Accepted**	Energy consumption growth has a positive and significant impact on environmental degradation.
H_2	*Economic development (GDP per capita) significantly increases CO_2 emissions in India.*	ARDL Long-Run Coefficient Test	t = **2.27**, p = **0.02**	**Accepted**	Rising economic activity contributes to higher emission levels.

H_3	*Fossil fuel consumption significantly increases CO_2 emissions.*	ECM Short-Run Test	t = **2.14**, p = **0.03**	**Accepted**	Fossil energy intensity is a major driver of short-run pollution.
H_4	*Renewable energy reduces CO_2 emissions in India.*	ARDL Short-Run Test	t = **–2.00**, p = **0.04**	**Accepted**	Renewables help mitigate environmental degradation.
	There exists a long-run equilibrium relationship between energy use, economic development, and CO_2 emissions.	ARDL Bounds Test	F = **5.20** > Upper bound **4.30**	**Accepted**	Long-run cointegration confirmed.

Source: Researcher's hypothesis testing results based on ARDL and ECM outputs using WDI and CEA datasets.

Table 4.5 presents hypothesis-testing outcomes for the study. Results indicate that energy expansion, economic development, and fossil fuel use significantly increase emissions, while renewable energy helps reduce them. The ARDL bounds test confirms a long-run equilibrium relationship. All hypotheses supporting the role of energy and economic factors in environmental degradation are statistically accepted, reflecting consistent evidence across long-run, short-run, and causality measures.

Major Finding :

1. **Most variables are non-stationary at level**, becoming stationary after first differencing (Table-1), confirming suitability for ARDL modeling.
2. **A strong long-run cointegration relationship** exists between CO_2 emissions, energy use, economic development, and population (Table-2).
3. **Long-run results show that total energy use, fossil fuel share, and GDP per capita significantly increase CO_2 emissions**, while renewable energy reduces emissions (Table-3).
4. **Short-run dynamics confirm similar patterns**, and the negative, significant ECT value shows CO_2 emissions adjust toward equilibrium at 40% each year (Table-4).
5. **All hypotheses are statistically supported**, confirming that energy expansion and economic development are major contributors to environmental degradation in India, whereas renewable energy mitigates pollution (Table-5).

Policy Suggestion :

1. **Accelerate renewable energy deployment** through subsidies, grid modernization, and storage investments.
2. **Reduce fossil-fuel dependence** by phasing out coal and expanding cleaner alternatives like natural gas and solar.
3. **Promote energy-efficient technologies** across industries to lower energy intensity.
4. **Integrate environmental regulations with economic planning** to balance growth and sustainability.

5. **Strengthen urban and transport reforms**—EV adoption, public transit, and city-level emission control policies.

This study empirically demonstrates that energy expansion and economic development are major determinants of environmental degradation in India. The long-run and short-run results from ARDL and ECM models reveal that rising energy consumption—especially from fossil fuels—significantly increases CO_2 emissions, highlighting the environmental cost of India's growth trajectory. In contrast, renewable energy shows a meaningful negative association with emissions, indicating its potential to mitigate environmental pressure. The existence of cointegration confirms a stable long-term relationship among CO_2 emissions, energy use, and economic growth. These findings underscore the urgency for India to shift from carbon-intensive energy pathways toward cleaner, sustainable alternatives. Strengthening energy efficiency, expanding renewable capacity, and regulating industrial emissions are essential to balance economic progress with environmental protection. Overall, the study provides strong evidence that India's environmental future hinges on strategic energy reforms aligned with sustainable development goals.

Limitations of the study :

This study primarily relies on secondary data, which may contain measurement gaps or reporting inconsistencies. The analysis uses macro-level indicators, limiting the ability to capture sector-specific variations in emissions. The study focuses on CO_2 as the main proxy for environmental degradation, excluding other pollutants. Additionally, the modeling approach may not fully incorporate structural breaks or policy shocks. Finally, results are sensitive to variable selection and may differ with alternative datasets or methodological choices.

Scope for further Research :

Future research can incorporate regional or state-level data to understand spatial differences in energy–environment relationships. Expanding environmental indicators to include particulate matter, ecological footprint, or water pollution would enrich the analysis. Advanced models such as nonlinear ARDL, machine learning forecasting, or panel data comparisons with emerging economies may offer deeper insights. Further studies can also explore the impact of renewable energy policies, technological innovations, and carbon pricing mechanisms on India's long-term environmental sustainability.

Author contributions :

The author conceptualized the study, collected secondary data, performed econometric analysis, interpreted the results, and prepared the manuscript. All sections—including introduction, methodology, analysis, findings, and conclusions—were independently developed and reviewed to ensure academic clarity, accuracy, and coherence.

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Conflict of interest :

The author declares no conflict of interest, and all analyses were conducted objectively and independently.

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