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Driving Sustainable Growth: The Integration Between Renewable Energy, Carbon Footprint and Economic Expansion in India

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ABSTRACT: This study examines the impact of renewable energy consumption on economic growth and carbon emissions in India over the period 2000–2023. Using annual time-series data sourced from the World Bank, IEA, and MNRE, the analysis employs the Autoregressive Distributed Lag (ARDL) bounds testing approach to investigate the short-run and long-run relationships among GDP, renewable energy consumption and CO_2 emissions per capita. Stationarity tests (ADF and PP) confirmed a mixed order of integration, validating the ARDL model application. The findings reveal a positive and significant impact of renewable energy consumption on economic growth, while carbon emissions negatively affect GDP performance. The Error Correction Term (ECT) confirms rapid convergence towards the long-run equilibrium. Diagnostic tests indicate that the model is free from serial correlation, heteroscedasticity and structural instability. Policy recommendations include scaling up renewable investments, promoting decentralised renewable systems, modernising energy storage infrastructure, and implementing carbon pricing mechanisms. Examples from Germany, Sweden, Bangladesh, and Australia provide practical lessons for India's transition to a low-carbon economy. The study adds to the empirical evidence on the green growth nexus and offers actionable insights for policymakers striving toward sustainable development.

KEYWORDS: Renewable Energy, Economic Growth, Carbon Emissions, ARDL Model, Sustainable Development
JEL CODES: Q42, O44, Q53

1. INTRODUCTION

In the 21st century, the world has witnessed an urgent call for climate action, driven by rising global temperatures, extreme weather events, and unsustainable fossil fuel dependence. India, as the third-largest emitter of carbon dioxide, faces a dual challenge—sustaining rapid economic growth while mitigating environmental degradation. To reconcile growth with sustainability, India has aggressively pursued renewable energy (RE) as a key pillar in its development strategy. From the launch of the National Solar Mission in 2010 to the recent push toward achieving 500 GW of non-fossil fuel capacity by 2030, the country's renewable energy narrative has shifted from aspiration to action.

As per data from the Ministry of New and Renewable Energy (MNRE), India's installed renewable energy capacity increased from just 18,000 MW in 2000 to approximately 174,000 MW in 2023, accounting for nearly 40% of the nation's total installed power capacity. Simultaneously, India's GDP has expanded from $476 billion in 2000 to $3.22 trillion in 2023 (World Bank, 2024), marking a period of high growth and industrial acceleration. However, the environmental cost of this expansion is evident in India's rising CO_2 emissions, which surged from 1.1 metric tons per capita in 2000 to around 1.9 metric tons in 2022.

Table 1: Key Indicators of India's Energy-Economy-Emission Nexus (2000–2023)

Year	Installed RE (MW)	RE Consumption (TWh)	GDP (USD)	CO_2/capita (tons)	GDP Growth (%)
2000	18,000	50	476B	1.1	5.6
2010	45,000	130	1.68T	1.5	8.5
2020	1,20,000	260	2.87T	1.8	4.2
2023	1,74,000	300	3.22T	1.9	8.2

Source: MNRE, World Bank, IEA, Author's Compilation)

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1.1. India’s Transition to Clean Energy

India's policy direction has witnessed a paradigm shift, moving beyond solar and wind promotion to integrated clean energy frameworks. The PLI Scheme for High-Efficiency Solar Modules, the PM-KUSUM Scheme, and India’s Net Zero 2070 commitment announced at COP26 reflect this strategic alignment. Furthermore, initiatives like Green Hydrogen Mission and carbon trading mechanisms are being positioned to decouple economic growth from environmental harm.While India’s renewable energy investments are commendable, the empirical relationship between renewable energy deployment, carbon footprint reduction, and economic growth remains under explored. Most existing literature either focuses narrowly on GDP or CO_2 emissions without assessing the triangular interlinkages among energy transition, emissions reduction, and economic performance. Moreover, it remains unclear whether India’s clean energy transition has begun to decouple carbon emissions from growth, or whether rising renewable energy merely supplements existing fossil-fuel-driven output. This study, therefore, aims to bridge this gap by analysing the impact of renewable energy on India’s economic growth and carbon emissions, using empirical data from 2000–2023 and robust econometric techniques.

2. LITERATURE REVIEW

The global discourse began gaining prominence with Sadorsky (2009), who highlighted that in emerging markets, renewable energy demand rises with income growth, suggesting a direct elasticity between GDP and RE consumption. Building on this, Apergis and Payne (2010) conducted a panel study across 20 OECD countries and confirmed a bidirectional relationship between renewable energy consumption and economic growth in both short and long run

Further refinement came through Shahbaz et al. (2015), who employed multivariate models across developing nations and demonstrated that while renewable energy helps reduce emissions, its growth-inducing potential is amplified when combined with technological investment. Meanwhile, Bhattacharya et al. (2016) emphasised that in OECD countries, renewable energy not only supported economic expansion but also improved environmental quality — making it a win-win option for sustainable development

In non-OECD contexts like Tunisia and Turkey, Sebri and Ben-Salha (2014) and Ocal and Aslan (2013) respectively, confirmed that renewable energy acts as a growth catalyst, but cautioned that the relationship may be unidirectional — from energy to GDP — in cases lacking supportive institutional frameworks

China’s case, studied by Lin and Moubarak (2014), reveals that clean energy significantly curbs CO_2 emissions while sustaining economic growth — particularly when guided by central policy instruments. These findings set a precedent for emerging economies like India, where the stakes are even higher due to rapid urbanisation and industrial scale.

Turning to India, Paramati et al. (2017) used Fully Modified OLS and showed that clean energy investment is positively associated with long-term GDP growth, urging stronger policy focus on green infrastructure. Similarly, Raghutla and Chittedi (2020) deployed a VECM approach and found evidence of long-run co-integration among renewable energy use, GDP, and CO_2 emissions, suggesting that India is on the cusp of a low-carbon growth transition [DOI: 10.1007/s11356-020-07729-5].

Supporting this, Chandran and Tang (2018) discovered a bidirectional causality between RE and GDP in India, implying that not only does RE contribute to growth, but growing income levels also fuel RE adoption. Sapkota and Bastola (2017) further extended this link by showing that electricity consumption, inclusive of renewables, drives industrial productivity in India [DOI: 10.1016/j.energy.2017.02.078].

The environmental lens is enriched by Bhat (2020), who emphasised the role of RE in mitigating India’s rising carbon emissions without compromising economic growth. The study argued for integrating RE within climate policy frameworks, especially under India's Nationally Determined Contributions (NDCs)

Globally, Nguyen and Kakinaka (2019) reinforced the findings from Southeast Asia, asserting that RE consumption leads to both economic advancement and environmental improvement, especially when paired with FDI and R&D. Jebli et al. (2016), examining agricultural economies, suggested that RE helps promote green productivity, particularly when rural electrification is involved. Despite this growing consensus, a clear gap remains in understanding the simultaneous interplay between renewable energy adoption, carbon footprint mitigation, and economic expansion — especially in the Indian context, where the transition is happening at scale and speed. While most studies assess two-variable relationships, few examine the three-way nexus with long-run data and advanced modelling techniques. This research addresses this void by empirically examining the impact of renewable energy on India’s economic growth and carbon emissions, using comprehensive data from 2000 to 2023.

3. RESEARCH OBJECTIVES

1. To empirically analyse the impact of renewable energy consumption on economic growth and carbon emissions in India during the period 2000–2023.
2. To evaluate the long-run and short-run dynamics between renewable energy development, economic performance, and environmental sustainability using the ARDL modelling approach.

4. METHODOLOGY

4.1. Data and Time Period

This study employs annual time-series data for India covering the period **2000 to 2023**. The selected timeframe captures significant policy shifts in India's energy sector, including the launch of the National Solar Mission (2010), the Intended Nationally Determined Contributions (2015), and the Net Zero 2070 pledge (COP26, 2021). These years provide a comprehensive view of India's renewable energy expansion and its macroeconomic and environmental outcomes.

4.2. Data Sources and Variables

The present study utilises annual time-series data for India spanning the period from 2000 to 2023. The key variables employed in the analysis include Renewable Energy Consumption (REC), Installed Renewable Energy Capacity (RECAP), Gross Domestic Product (GDP), GDP Growth Rate (GDPGR), Carbon Dioxide Emissions per Capita (CO_2PC), Total Carbon Dioxide Emissions (TCO_2), and Energy Intensity of GDP (EINT). Renewable Energy Consumption (REC), measured in terawatt-hours (TWh), and Installed Renewable Energy Capacity (RECAP), measured in megawatts (MW), are sourced primarily from the International Energy Agency (IEA), the Ministry of New and Renewable Energy (MNRE), Government of India, and the Central Electricity Authority (CEA). Economic indicators such as Gross Domestic Product (GDP) at constant US dollars and GDP Growth Rate (%) are obtained from the World Bank and the Ministry of Statistics and Programme Implementation (MOSPI). Environmental indicators, including Carbon Dioxide Emissions per Capita (CO_2PC) and Total CO_2 Emissions (TCO_2), are sourced from the World Bank, the United Nations Framework Convention on Climate Change (UNFCCC), and the Global Carbon Atlas. Additionally, Energy Intensity of GDP (EINT), reflecting energy usage efficiency, is retrieved from the IEA and World Bank databases. All variables have been cleaned and transformed appropriately, with natural logarithms applied to select variables to ensure linearity, stabilise variance, and facilitate elasticity interpretation in the econometric modelling.

4.3. Data Techniques and Tools

To investigate the relationship between renewable energy consumption, carbon emissions, and economic growth in India, the study adopts a multi-stage econometric strategy. Initially, the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests are applied to ascertain the stationarity properties of the variables, ensuring that none of the series are integrated of order two, I(2), which would otherwise invalidate the ARDL approach. Following the confirmation of stationarity at levels or first difference, the Autoregressive Distributed Lag (ARDL) bounds testing approach developed by Pesaran et al. (2001) is employed to test for the existence of a long-run co-integration relationship among the variables. The ARDL method is chosen due to its flexibility in handling variables integrated at different levels (I(0) and I(1)), and its suitability for small sample sizes such as the dataset used in this study.

Upon establishing co-integration, the study estimates both the long-run equilibrium coefficients and the short-run dynamics using the associated Error Correction Model (ECM) derived from the ARDL framework. The ECM term captures the speed of adjustment, indicating how quickly deviations from the long-run equilibrium are corrected in subsequent periods. Moreover, to validate the robustness of the estimated models, a series of diagnostic tests are conducted, including the Breusch-Godfrey Serial Correlation LM Test for autocorrelation, the ARCH Test for heteroscedasticity, and the Jarque-Bera Test for normality of residuals. Additionally, CUSUM and CUSUMSQ stability tests are applied to examine the structural stability of the models over the sample period.

All econometric estimations are carried out using E-Views 12 software, while preliminary data visualisation and transformation processes are undertaken through Microsoft Excel and Python. This rigorous methodological framework ensures that the empirical findings are statistically reliable, theoretically grounded, and policy relevant.

5. RESULTS AND DISCUSSION

5.1. Stationarity and Unit Root Tests

Before proceeding to model estimation, the stationarity of the variables was tested using the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests.

Table 2: Stationarity Test Results (ADF and PP Tests)

Variables	Level	1st Difference	Integration Order
GDP	Non-Stationary	Stationary	I(1)
Renewable Energy Consumption (REC)	Stationary	—	I(0)
Installed Renewable Capacity (RECAP)	Non-Stationary	Stationary	I(1)
CO_2 Emissions per Capita (CO_2PC)	Non-Stationary	Stationary	I(1)
Energy Intensity (EINT)	Stationary	—	I(0)

Source: Authors Calculation

The results from both the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests confirm that the variables exhibit a mixed order of integration. Specifically, Renewable Energy Consumption (REC) and Energy Intensity (EINT) are stationary at level [I(0)], whereas GDP, Installed Renewable Capacity (RECAP), and CO_2 Emissions per Capita (CO_2PC) become stationary after first differencing [I(1)]. No variable is integrated of order two [I(2)], validating the suitability of applying the ARDL bounds testing approach for co-integration analysis.

5.2. ARDL Bounds Test for Co-integration

The ARDL bounds test confirmed the presence of a long-run co-integration relationship among Renewable Energy Consumption, Carbon Emissions, and Economic Growth.

Table 3: ARDL Long-Run and Short-Run Results

Variables	Long-Run Coefficient	T-stats	Short run coefficient	T-stats
REC (Renewable Energy Consumption)	0.423***	4.27	0.215**	2.54
RECAP (Installed Renewable Capacity)	0.132*	1.89	0.071	1.42
CO_2PC (CO_2 Emissions per Capita)	-0.361***	-3.78	-0.205**	-2.13
ECT(-1) (Error Correction Term)	-0.511***	-6.12	—	—
Constant	2.105**	2.37	—	—

***$p < 0.01$; **$p < 0.05$; *$p < 0.10$

Source: Author's estimation based on ARDL model.

Firstly, Renewable Energy Consumption (REC) has a positive and highly significant impact on economic growth in both the long run (coefficient = 0.423, $p < 0.01$) and the short run (coefficient = 0.215, $p < 0.05$). This suggests that an increase in renewable energy usage not only fosters immediate economic expansion but also strengthens India's long-term growth trajectory. This finding aligns with global trends where renewable investments are recognised as catalysts for green economic development.

Secondly, Installed Renewable Capacity (RECAP) also positively influences GDP, although its effect is weaker and only significant at the 10% level in the long run. This implies that while installing renewable infrastructure is important, actual consumption and integration into the energy system is what truly drives economic benefits.

Thirdly, CO_2 emissions per capita (CO_2PC) have a negative and statistically significant impact on GDP in both the long and short run. A one percent increase in carbon emissions leads to a 0.36% decrease in GDP in the long run, emphasising that environmental degradation acts as a drag on sustainable economic performance. This supports the theory that high emissions impose social, health, and environmental costs that hinder productivity and growth.

The **Error Correction Term (ECT)** is negative and highly significant (-0.511), indicating that any deviations from the long-run equilibrium are corrected by approximately 51% each year. This robust adjustment speed implies that India's economy responds quickly to shocks in energy consumption or environmental performance, gradually restoring long-run balance.

Overall, these findings affirm that renewable energy development not only promotes economic growth but also assists in reducing the carbon footprint, offering a dual advantage crucial for India's sustainable development agenda.

5.3. Error Correction Model (Short-Run Dynamics)

Table 4: ECM (Short-Run Dynamics)

Variables	Short run Coefficient	T-stats	P-value
ΔREC	0.215**	2.54	0.018
ΔRECAP	0.071	1.42	0.165
ΔCO_2PC	-0.205**	-2.13	0.041
ECT(-1)	-0.511***	-6.12	0.000

Source: Author's Calculation

Δ indicates first difference. ***$p < 0.01$; **$p < 0.05$; *$p < 0.10$

The Error Correction Model (ECM) results indicate that Renewable Energy Consumption (REC) exerts a positive and significant short-run impact on GDP growth (coefficient = 0.215, $p < 0.05$). In contrast, changes in CO_2 emissions negatively impact GDP in the short term, highlighting the short-run vulnerability of economic performance to environmental degradation. The Error Correction Term (ECT) is negative and highly significant (-0.511, $p < 0.01$), confirming that any short-term disequilibrium is corrected by approximately 51% annually, ensuring convergence towards the long-run equilibrium path.

5.4. Diagnostic Tests and Model Stability

Robustness tests used for confirming the model stability are : Breusch-Godfrey Serial Correlation LM test for serial correlation. ARCH test for confirming homoscedasticity. Jarque-Bera test for normality of data series and lastly CUSUM and CUSUMSQ for stability of model.

Table 5: Diagnostic Test Results

Test	Test statistic	P-value	Conclusion
Breusch-Godfrey Serial Correlation LM Test	1.42	0.231	No Serial Correlation
ARCH Heteroscedasticity Test	0.87	0.356	No Heteroscedasticity
Jarque-Bera Normality Test	1.28	0.527	Residuals are Normally Distributed
CUSUM Test	—	Stable	Model is Stable
CUSUMSQ Test	—	Stable	Model is Stable

Source: author's Calculation

The model passes all major diagnostic tests, reinforcing its statistical robustness. The Breusch-Godfrey LM test indicates the absence of serial correlation among residuals, and the ARCH test confirms homoscedasticity. The Jarque-Bera test validates the normal distribution of residuals, fulfilling classical OLS assumptions. Stability plots, including the CUSUM and CUSUMSQ tests, reveal that the estimated coefficients remain within critical bounds over the sample period, indicating **structural stability** of the model.

6. CONCLUSION

The present study empirically investigated the relationship between renewable energy consumption, carbon emissions, and economic growth in India over the period 2000–2023, employing the Autoregressive Distributed Lag (ARDL) modelling approach. The results provide robust evidence of a long-run co-integration relationship among the variables. Specifically, the findings reveal that renewable energy consumption positively contributes to India's economic growth, both in the short and long run. At the same time, carbon emissions exert a significant negative influence on GDP growth, highlighting the economic costs associated with environmental degradation.

The study also confirms the structural stability of the model and the rapid correction mechanism towards equilibrium, suggesting that India's energy-economy-environment system is dynamic and responsive. The Error Correction Term (ECT) showed a convergence speed of approximately 51% annually, underscoring the resilience of the economy to energy and environmental shocks.

These results reinforce the critical role of renewable energy in achieving sustainable economic development. The expansion of renewable energy infrastructure, alongside the reduction of carbon emissions, appears essential not only for India's environmental goals but also for fostering inclusive and resilient economic growth. Importantly, the study fills an existing gap in the literature by examining the triangular nexus among renewable energy, carbon footprint reduction, and GDP in an emerging economy context. While the empirical findings are encouraging, they also emphasise the need for proactive and strategic policy interventions to maximise the developmental benefits of renewable energy while minimising ecological harm. Future policies must prioritise scaling up renewable energy investments, fostering technological innovation, ensuring grid integration, and strengthening regulatory frameworks to sustain the momentum towards a low-carbon economy.

7. POLICY IMPLICATIONS

1. Scale Up Renewable Energy Investments

Example: Germany's Enervierende (Energy Transition)

Germany's long-term policy to heavily invest in renewables has led to over 50% of its electricity generation coming from renewable sources (BMWK, 2023). India can replicate similar models by providing subsidies, tax breaks, and long-term financing schemes for solar and wind projects, especially at the decentralised rural level.

2. Promote Decentralised Renewable Systems

Example: Bangladesh's Solar Home System (SHS) Program

Bangladesh successfully deployed over 4.5 million solar home systems in off-grid rural areas, providing clean energy to 20 million people (World Bank, 2022). India, especially in remote states like Jharkhand, Chhattisgarh, and parts of the Northeast, can adopt a similar decentralised energy deployment model.

3. Strengthen Grid Modernisation and Storage Infrastructure

Example: Australia's Hornsdale Power Reserve (Tesla's Big Battery)

Australia integrated a massive battery storage system that stabilised its renewable grid fluctuations effectively (South Australia Government, 2021). India must invest in large-scale battery storage to manage the intermittency of renewable sources like solar and wind.

4. Implement Carbon Pricing Mechanisms

Example: Sweden's Carbon Tax Success

Sweden introduced one of the world's first and highest carbon taxes in the early 1990s, leading to a 27% reduction in emissions while growing its GDP by 75% (IEA, 2022). India could explore moderate carbon pricing for high-emission industries to drive them towards clean technologies.

5. Encourage Research and Innovation in Green Technologies

Example: USA's ARPA-E Program

The Advanced Research Projects Agency-Energy (ARPA-E) in the U.S. funds disruptive green energy technologies. India can establish similar platforms to boost R&D in next-generation renewables like green hydrogen, offshore wind, and floating solar.

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