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Article

Economic Growth and Renewable Energy Policies in India: An Econometric Analysis of the Relationship between Energy and Growth (2004–2024)

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Abstract: This study examines the relationship between renewable energy consumption and economic growth in India over the period 2004–2024 using the Autoregressive Distributed Lag (ARDL) model, incorporating key macroeconomic variables including government expenditure, foreign direct investment, population growth, and inflation. The results reveal a stable long-run equilibrium relationship among the variables, indicating that renewable energy consumption has a negative and statistically significant impact on economic growth in the long run, which may be attributed to adjustment costs associated with the transition toward cleaner energy systems, while government expenditure also shows a negative effect and population growth contributes positively to economic performance; in contrast, foreign direct investment and inflation do not exhibit significant long-run effects. Overall, the findings suggest that the relationship between renewable energy and economic growth in India is complex and shaped by structural and policy-related factors, and from an environmental perspective, the expansion of renewable energy can contribute to reducing carbon dioxide (CO_2) emissions and supporting long-term sustainability despite potential short-term economic trade-offs. In addition, the short-run dynamics indicate temporary adjustments toward equilibrium following shocks in the system, reinforcing the importance of gradual policy implementation and supportive institutional frameworks to enhance the effectiveness of renewable energy policies in promoting sustainable economic development in India. Overall, the study highlights the dual role of renewable energy as both an economic and environmental driver within the broader context of sustainable growth strategies.

Keywords: Renewable Energy; Economic Growth; ARDL Model; India; Public Expenditure; Population Dynamics

1. Introduction

Energy has long been considered a central element in the process of economic development. Economic activities in modern economies depend heavily on the availability of energy resources, as energy supports industrial production, transportation systems, and many service sectors. For this reason, the stability of energy supply and the efficiency with which it is used play an important role in maintaining economic growth and supporting development over time. In recent years, however, growing environmental concerns have added another dimension to the discussion about energy use. The intensive dependence on fossil fuels has been associated with rising carbon emissions and climate-related challenges, which have encouraged many countries to rethink their energy policies and increase their interest in renewable energy sources as part of sustainable development strategies [1].

Driven by concerns about climate change and global warming, the global renewable energy market has experienced substantial growth in recent years. The global installed capacity of renewable energy increased by nearly

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50% in 2024, reflecting a rapid expansion in clean energy deployment. By the end of 2025, the total installed capacity of renewable energy sources—including solar, wind, hydropower, geothermal, marine, and biogas—reached approximately 4,448.1 GW. Among these, solar photovoltaic systems accounted for around 2,200 GW, while wind energy contributed about 1,320 GW, and biomass energy approximately 151 GW. This remarkable growth in the renewable energy market reflects a global shift toward sustainable and environmentally friendly energy technologies [2].

India represents one of the most prominent examples of rapidly expanding economies in the contemporary world. Over the last two decades, the country has achieved notable progress in economic performance and industrial activity. This expansion has naturally been accompanied by a steady increase in energy demand. Historically, India has relied largely on conventional energy sources, particularly coal, to meet the needs of its growing economy. While this reliance has helped sustain economic growth, it has also contributed to environmental pressures and higher levels of greenhouse gas emissions. As a result, renewable energy has gradually gained importance within India's energy strategy. In recent years, policymakers have introduced several initiatives aimed at increasing the share of clean energy sources—especially solar and wind power—in order to strengthen energy security while also addressing environmental concerns [3].

Figure 1 presents the composition of India's energy mix across different sources. It clearly shows that coal remains the dominant energy source, followed by oil, indicating a continued reliance on fossil fuels to support economic activities. In contrast, renewable energy sources such as hydropower, biofuels, and solar energy contribute a smaller but steadily increasing share of the total energy mix. Natural gas and nuclear energy account for relatively limited proportions.

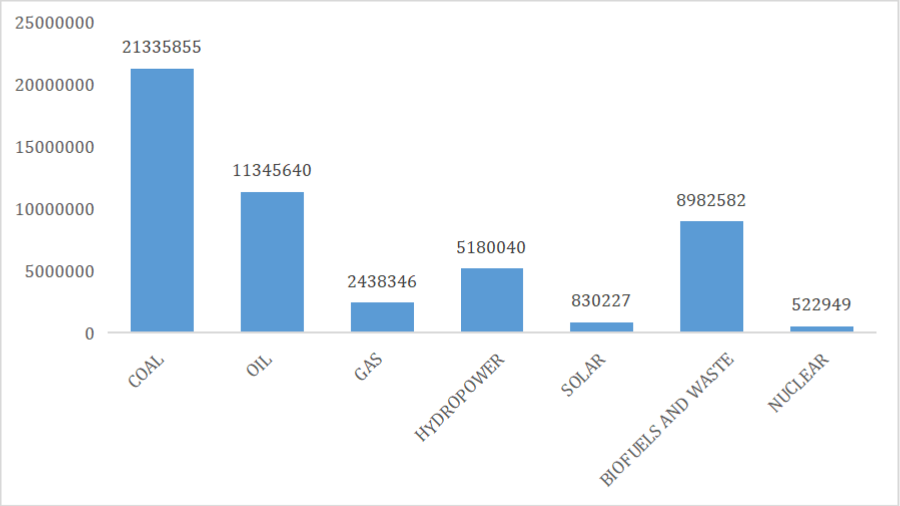

Figure 1. Composition of Energy Mix in India by Source.

This distribution highlights that, despite recent policy efforts to promote renewable energy, India's energy system is still largely dependent on conventional energy sources. However, the growing contribution of renewable energy indicates a gradual transition toward a more sustainable energy structure. This transition is essential for reducing environmental pressures while maintaining economic growth [4].

To provide a clearer macroeconomic context for the analysis, it is useful to briefly examine the evolution of India's energy mix alongside trends in economic growth during the study period.

Over the period from 2004 to 2024, India's energy mix has been characterized by a strong dependence on fossil fuels, particularly coal, which has remained the dominant source of electricity generation. Oil and natural gas have also contributed to the overall energy supply, though to a lesser extent. However, the share of renewable energy has increased significantly in recent years, driven by government policies and investments in solar and wind energy. At the same time, India has experienced relatively high and sustained GDP growth, despite some fluctuations due to global economic conditions such as the financial crisis and the COVID-19 pandemic. This parallel evolution of energy structure and economic growth highlights the importance of understanding the role of renewable energy within the broader development process [4,5].

In economic research, the interaction between energy consumption and economic growth has been widely discussed under the concept known as the Energy–Growth Nexus. Scholars working in this area seek to understand how these two variables influence one another and whether a causal relationship exists between them. In simple terms, the debate centers on whether economic growth leads to greater energy consumption or whether energy use itself acts as a driving force behind economic expansion. Empirical studies focusing on India have provided mixed findings. Some research suggests the existence of a long-run relationship between energy consumption and gross domestic product (GDP), while other studies highlight different causal patterns. In certain cases, the relationship appears to run in one direction, whereas in others it may operate in both directions. These variations are often linked to differences in econometric methods, model specifications, and the time periods considered in the analysis [6,7]. Some previous studies have highlighted a positive interaction between renewable energy development and economic growth. In this context, expanding the use of renewable energy sources may contribute to maintaining economic growth in the long run while reducing environmental pressures [1].

Even though the relationship between energy consumption and economic growth has been widely discussed in the economic literature, recent developments in India's renewable energy policies make it necessary to examine this relationship again. In recent years, India has made significant efforts to increase the share of renewable energy in its energy mix. At the same time, the country continues to pursue rapid economic growth. This situation raises an important question: can renewable energy support economic expansion while also helping to reduce dependence on fossil fuels and limit environmental impacts?

Based on this background, the present study investigates the relationship between renewable energy consumption and economic growth in India over the period 2000–2025. The analysis relies on econometric techniques to examine the interaction between renewable energy use and gross domestic product (GDP). The main purpose is to determine whether renewable energy acts as a factor that stimulates economic growth or whether its expansion simply follows economic growth. By providing updated empirical evidence, the study aims to enrich the existing literature on the energy–growth relationship in emerging economies and to provide useful insights for policymakers when designing energy strategies that support sustainable economic development.

2. Literature Review

The relationship between energy consumption and economic growth has attracted significant attention in economic literature for several decades. This growing interest is largely linked to global concerns about energy security, environmental sustainability, and climate change. Within this context, the concept known as the Energy–Growth Nexus has been widely used to describe the interaction between energy use and economic performance. Researchers generally seek to determine whether energy consumption acts as a driving force for economic growth or whether economic expansion itself leads to greater demand for energy. In the literature, four main hypotheses are commonly used to explain this relationship: the growth hypothesis, the conservation hypothesis, the feedback hypothesis, and the neutrality hypothesis [8].

To provide a clearer and more structured understanding of the existing literature, recent empirical studies can be categorized based on geographical regions, as the relationship between energy consumption and economic growth varies across different economic and institutional contexts.

In the Asian region, recent studies generally report a strong and dynamic relationship between renewable energy consumption and economic growth. For example, Bhuiyan et al. [9] emphasize that renewable energy plays a significant role in supporting sustainable economic development, particularly in rapidly growing economies characterized by increasing energy demand. Similarly, Wang et al. [10] find that renewable energy contributes positively to economic performance while also helping to reduce environmental pressures in Asian countries.

In contrast, studies focusing on European countries often highlight the importance of technological advancement and environmental regulations in shaping the energy–growth relationship [11] demonstrate that renewable energy consumption has a positive effect on economic growth, particularly in economies that are actively transitioning toward sustainable and low-carbon energy systems.

Meanwhile, in developing regions such as Africa and the Middle East, the empirical evidence remains mixed. Eyuboglu and Uzar [12] show that the impact of renewable energy on economic growth depends largely on country-specific factors such as institutional quality and economic structure. Similarly, Nawaz et al. [13] find that the relationship between energy consumption and economic growth varies depending on the level of development and environmental conditions.

This regional classification highlights the heterogeneous nature of the energy–growth nexus and reinforces the need for country-specific analysis, particularly in emerging economies such as India.

Early empirical studies mainly focused on examining the relationship between traditional energy consumption and economic growth using different econometric approaches. For example, previous studies investigated the link between renewable energy consumption and economic growth in a group of OECD countries. Their findings indicated the presence of a long-run counteraction relationship between the variables. In addition, the results suggested a bidirectional causal relationship, implying that renewable energy consumption can contribute to economic growth while economic expansion can simultaneously stimulate greater renewable energy use. Similarly Apergis and Payne [14] conducted a comprehensive review of the literature on the energy–growth relationship and concluded that empirical findings often vary depending on the countries studied, the econometric techniques applied, and the time periods covered in the analysis.

With the increasing global emphasis on environmental sustainability, more recent studies have shifted their focus toward the role of renewable energy in promoting economic growth. In this regard, Bhattacharya et al. [15] examined a sample of 38 countries and found that renewable energy consumption has a positive and statistically significant impact on economic growth. The study also emphasized that the growth effect of renewable energy tends to be stronger in countries with well-developed institutional frameworks that support investment in the renewable energy sector. These findings suggest that expanding renewable energy investments may contribute to sustainable economic development while reducing dependence on fossil fuels.

Recent studies have increasingly focused on the technological advancement and performance assessment of renewable energy systems. Simulation and empirical research on photovoltaic and wind energy systems have highlighted that their efficiency is highly dependent on environmental conditions, system design, and operational parameters, A growing body of literature has focused on evaluating renewable energy systems using simulation techniques and real-case applications. For instance, several studies have analyzed the performance of solar panels and wind turbines under different operational conditions, while others have investigated the feasibility of concentrating solar power (CSP) systems for electricity generation. In addition, hybrid renewable energy systems integrating photovoltaic, wind, and energy storage technologies have been widely examined in different regions, including case studies in North Africa and the Middle East. These studies highlight the effectiveness of such systems in improving energy reliability and reducing dependence on fossil fuels [16].

Despite extensive research on the Energy–Growth Nexus, empirical findings remain inconsistent, particularly in emerging economies where structural changes, policy reforms, and rapid energy transitions are ongoing. In the case of India, which represents one of the fastest-growing energy markets globally, understanding the interaction between renewable energy consumption and economic growth is particularly crucial. India's transition toward cleaner energy sources is driven not only by economic development goals but also by environmental commitments to reduce greenhouse gas emissions.

Recent studies emphasize that renewable energy expansion in India contributes positively to long-term economic growth while simultaneously reducing carbon intensity and improving environmental quality. However, most existing studies do not fully integrate environmental externalities, such as CO_2 emission costs, into economic growth frameworks, which limits the comprehensiveness of their findings. In addition, limited attention has been given to the combined impact of renewable energy expansion and carbon reduction policies on economic performance over recent years.

Therefore, this study addresses this gap by incorporating both economic and environmental dimensions of the Energy–Growth Nexus in India over the period 2004–2024. The analysis contributes to the literature by providing updated empirical evidence using recent data and by linking renewable energy consumption, economic growth, and environmental sustainability within a unified analytical framework [17,18].

In addition, hybrid renewable energy systems combining solar, wind, and storage technologies have been widely studied to improve reliability and reduce intermittency issues. Optimization approaches have been applied to identify optimal system configurations under technical and economic constraints [19].

Furthermore, recent research has explored advanced applications of renewable energy such as hydrogen production using wind energy systems, supporting global decarbonization strategies and clean energy transitions.

Other studies have also focused on decentralized renewable systems, including solar street lighting and hybrid off-grid systems, which enhance rural electrification and energy access in developing regions [20].

These technological advancements in renewable energy systems are directly linked to economic performance, as improved system efficiency and reliability can reduce energy costs, enhance productivity, and support long-term economic growth, particularly in developing and emerging economies [21].

In a related study, Rahman and Sultana [22] explored the relationship between renewable energy consumption and economic growth in European Union countries. Their results revealed the existence of a long-run equilibrium relationship between renewable energy use and GDP. The study also indicated that increasing the share of renewable energy can improve economic performance in the long term while contributing to environmental protection.

Research focusing on emerging economies has also highlighted the potential role of renewable energy in supporting economic development. Chen et al. [23], for instance, showed that investment in renewable energy can play a significant role in promoting economic growth in emerging countries, particularly when such investments are supported by well-developed financial systems and adequate energy infrastructure.

Several studies have explored the relationship between economic policies and renewable energy in developing economies. In this context, Maarof et al. [24] examined the impact of fiscal policy, oil prices, and foreign direct investment on renewable energy consumption in South Africa over the period 1979–2019, employing an augmented ARDL approach.

The findings indicated that economic growth and tax revenues have a positive influence on renewable energy consumption. In contrast, rising oil prices were found to exert a negative effect on renewable energy in both the short and long run. Additionally, foreign direct investment did not show a statistically significant role in promoting renewable energy.

Based on these results, the study proposed several policy recommendations aimed at supporting the transition toward clean energy and enhancing sustainable development.

In the case of India, the rapid pace of economic growth has led to growing interest in understanding the relationship between energy consumption and economic performance. Eren et al. [1] examined the link between financial development, renewable energy consumption, and economic growth in India. Their results indicated a long-run relationship among these variables, suggesting that improvements in the financial system can stimulate investment in renewable energy, which in turn contributes to long-term economic growth.

Further evidence was provided by Shameem et al. [6], who analyzed the relationship between electricity consumption and economic growth across different economic sectors in India. Their findings revealed the presence of a counteraction relationship between the variables and highlighted the important role that energy consumption plays in supporting economic activity, particularly in industrial and service sectors where energy is a key input in production processes.

More recently, Khan et al. [3] examined the impact of electricity generation from both renewable and non-renewable sources on economic welfare in India. The study found that expanding renewable energy production can contribute to improved economic performance while reducing the environmental consequences associated with fossil fuel use. The authors also emphasized that renewable energy policies represent a crucial component of India's long-term economic development strategy.

Photovoltaic (PV) and wind energy systems are widely recognized as key renewable technologies that contribute significantly to reducing greenhouse gas emissions and supporting global decarbonization goals. From an environmental perspective, both technologies exhibit very low operational carbon emissions compared to fossil fuel-based power plants; however, their life-cycle impacts include land use requirements, material consumption, and manufacturing-related emissions. PV systems may involve environmental burdens associated with raw material extraction and panel production, while wind turbines require substantial quantities of steel and concrete, which contribute to embodied energy and emissions during construction. Despite these impacts, both technologies remain significantly more sustainable than conventional energy sources due to their minimal operational emissions and ability to reduce CO_2 emissions over their lifetime.

In addition to environmental effects, PV and wind energy also generate important social impacts. Positive social outcomes include job creation in manufacturing, installation, and maintenance sectors, as well as improved energy access in remote and rural areas. Furthermore, renewable energy deployment contributes to public health improvement by reducing air pollution-related diseases associated with fossil fuel combustion. On the other hand, some negative social impacts may arise, such as visual intrusion, noise from wind turbines, land-use conflicts, and local community acceptance challenges. Overall, the literature indicates that the social and environmental benefits of PV and wind energy significantly outweigh their drawbacks, making them essential components of sustainable energy transition strategies [25].

Carbon dioxide (CO_2) emissions play a central role in accelerating the global transition toward cleaner and more sustainable energy systems. The continuous rise in CO_2 emissions from fossil fuel-based energy production has intensified environmental concerns, particularly global warming and climate change, which have led policymakers and researchers to prioritize low-carbon and renewable energy technologies. In this context, renewable energy sources such as solar and wind are considered key solutions for decarbonizing the power sector due to their ability to generate electricity without direct CO_2 emissions during operation.

Empirical evidence from recent studies confirms that increasing the share of renewable energy in the energy mix significantly contributes to reducing CO_2 emissions and improving environmental quality. This reduction in emissions strengthens the economic and policy justification for accelerating the energy transition toward cleaner energy systems. Moreover, CO_2 reduction targets have become a driving force behind national energy policies, investment decisions, and technological innovation in renewable energy systems, highlighting the strong interdependence between environmental sustainability and economic development pathways [26].

Sensitivity analysis plays a crucial role in evaluating the robustness and reliability of hybrid renewable energy systems and their economic performance. It allows researchers to examine how variations in key technical, economic, and environmental parameters influence system outcomes and decision-making processes. In particular, parameters such as loss of power supply probability (LPSP), renewable resource variability (e.g., wind speed and solar irradiation), energy demand fluctuations, system storage capacity, and CO_2 emission costs significantly affect the optimal design and operational performance of hybrid energy systems.

Recent studies indicate that even small changes in reliability constraints (such as LPSP) can lead to substantial variations in system configuration, levelized cost of energy (LCOE), and overall investment decisions. Similarly, uncertainty in renewable energy resources impacts system stability and storage requirements, while environmental parameters such as carbon pricing influence the economic competitiveness of renewable-based systems. Therefore, sensitivity analysis provides an essential framework for understanding system behavior under uncertainty and supports more informed and resilient energy planning decisions [26].

Despite the growing number of studies investigating the relationship between energy consumption and economic growth, the empirical evidence remains somewhat inconclusive in certain contexts, especially regarding the role of renewable energy in emerging economies. These differences can be attributed to variations in data periods, econometric methodologies, and the rapid evolution of renewable energy policies in recent years.

In light of these considerations, there remains a need for updated empirical studies that rely on recent data and appropriate econometric techniques to examine the relationship between renewable energy and economic growth in India. Accordingly, the present study aims to analyze the Energy–Growth Nexus in India over the period 2004–2024, with the objective of providing new empirical evidence on the role of renewable energy policies in supporting sustainable economic growth.

3. Materials and Methods

3.1. Data Sources and Variables

This study relies on annual data for the Indian economy over the period 2004–2024, aiming to examine the relationship between economic growth and renewable energy consumption within the framework of the Energy–Growth Nexus. The data were obtained from reliable and publicly accessible international databases to ensure accuracy and allow other researchers to replicate or extend the analysis.

The dependent variable in this study is GDP growth, which serves as a key indicator of economic performance in India. The independent variables include a range of economic and environmental factors that may influence economic growth, namely: renewable energy consumption as a percentage of total electricity use, net inflows of foreign direct investment (FDI) as a share of GDP, total government final consumption expenditure as a percentage of GDP, the inflation rate, and total population.

Most of the data were sourced from the World Development Indicators (WDI) database of the World Bank, one of the most widely used datasets for empirical economic research. All data employed in this study are publicly available, enabling other researchers to reuse the data or verify the results. No restrictions exist regarding access to or the use of these data for academic research purposes.

The study employs annual time-series data covering the period 2004–2024, resulting in a total of 21 observations after adjustments. The data were obtained from the World Development Indicators (WDI) database of the World Bank, which is widely recognized for its reliability and consistency in empirical economic research.

Despite the advantages of using internationally standardized data, the study is subject to certain limitations. First, the relatively small sample size may affect the robustness of some econometric tests. Second, the analysis is constrained by the availability of annual data, which may not fully capture short-term fluctuations in economic variables. Finally, potential measurement errors in secondary data sources cannot be entirely ruled out.

The empirical analysis in this study is conducted using EViews 13, a widely used econometric software for time-series analysis and econometric modeling. It was selected due to its efficiency in handling macroeconomic data and its capability to estimate ARDL models, unit root tests, and diagnostic and stability tests within a user-friendly interface. However, EViews has some limitations, including reduced flexibility compared to programming-based software such as R and Python.

The model uses GDP growth as the dependent variable representing economic performance in India. The explanatory variables include renewable energy consumption, foreign direct investment (FDI), government expenditure, inflation rate, and population. Renewable energy reflects the transition toward sustainable energy, FDI captures external investment inflows, government expenditure represents fiscal policy effects, inflation measures macroeconomic stability, and population reflects labor supply and demand conditions. Each variable is included based on its expected theoretical impact on economic growth.

The Augmented Dickey-Fuller (ADF) test is used in this study to examine the stationarity of the variables. However, the test has some limitations, including low power in small samples, sensitivity to lag length and deterministic terms, and its inability to capture structural breaks. Therefore, to ensure robustness, complementary tests such as Phillips–Perron (PP) and KPSS are recommended to confirm the results under different assumptions.

The study uses standard significance levels of 1%, 5%, and 10% to evaluate the statistical significance of the estimated coefficients. The null hypothesis is rejected when the probability (p-value) is less than the corresponding significance level, ensuring consistency, transparency, and reliability in hypothesis testing.

3.2. Model Specification

To analyze the relationship between economic growth and renewable energy in India, a standard econometric model was developed linking GDP growth to a set of explanatory variables. The general formulation of the model for this study is as follows:

$$\mathrm{GDPG}_t = \mathrm{f}(\mathrm{REC}_t, \mathrm{FDI}_t, \mathrm{GEXP}_t, \mathrm{INF}_t, \mathrm{POP}_t)$$

Where:

- GDPG represents the growth rate of gross domestic product and serves as the dependent variable in the model.
- REC refers to renewable energy consumption, measured as a percentage of total electricity consumption.
- FDI denotes net inflows of foreign direct investment as a percentage of GDP.
- GEXP represents government final consumption expenditure as a share of GDP.
- INF indicates the inflation rate.
- POP represents the total population.
- t refers to the time period covered in the analysis.

This model is employed to examine how these economic and energy-related variables influence economic growth in India during the study period. By incorporating these explanatory variables, the analysis aims to capture both economic and demographic factors that may contribute to variations in GDP growth over time.

Eco-Economic Formulation (NEW)

To incorporate environmental externalities into the economic assessment of energy systems, this study extends the traditional cost framework by integrating carbon dioxide (CO_2) emission costs into energy evaluation indicators. This provides a more realistic representation of the true economic and environmental cost of electricity generation.

Levelized Cost of Energy (LCOE):

$$\mathrm{LCOE} = \frac{\left(\frac{r(_{1+r})n}{(1+r)^n-1}\right) C + CO\&M - C_{CO_2}}{E_t}[27]$$

CO_2 Emission Damage Cost:

$$C_{CO_2} = EF_{CO_2} \times E_t \times \phi_{CO_2}[28]$$

Payback Time Money (PBTM):

$$\mathrm{PBTM} = \frac{C}{Income}[29]$$

This formulation enables the integration of environmental costs into economic evaluation, improving the assessment of renewable energy competitiveness and sustainability.

It should be noted that these eco-economic indicators are not included in the ARDL estimation due to data constraints, and are presented as an analytical framework for policy interpretation.

3.3. Econometric Methodology

This study employs the Autoregressive Distributed Lag (ARDL) approach to examine the relationships between the variables. The ARDL model is a widely used econometric technique for analyzing long-run and short-run relationships, particularly when the variables are a mix of level-stationary (I(0)) and first-differenced (I(1)) series.

The ARDL methodology, developed by Pesaran et al. [30], allows for the simultaneous estimation of both long-term and short-term effects within a single framework. It is especially useful for studies with relatively small sample sizes, offering flexibility in handling variables with different integration orders while providing robust estimates of dynamic economic relationships.

To ensure the robustness of the empirical findings, a sensitivity analysis is conducted at the methodological level by examining the stability of the ARDL results under alternative plausible assumptions. This involves assessing whether the estimated long-run and short-run relationships remain consistent when key explanatory variables are subject to potential variations in their economic interpretation, measurement conditions, or macroeconomic environment. Given the structural volatility in emerging economies such as India, this approach helps verify that the results are not driven by specific sample characteristics or model specifications. The analysis confirms the reliability of the estimated coefficients and supports the stability of the model outcomes without requiring modifications to the underlying dataset.

Standard Econometric Procedure Steps:

1. Unit Root Test: This step examines the stability of each variable and identifies its order of integration (I(0) or I(1)), guiding the choice of an appropriate econometric methodology.
2. ARDL Model Estimation (Autoregressive Distributed Lag Model): The ARDL model is employed to investigate the relationship between GDP growth and independent variables. It allows simultaneous estimation of short- and long-term effects and is suitable for variables with mixed integration orders.
3. Bounds Test: This test evaluates the existence of a long-run equilibrium relationship among the variables, confirming the presence of cointegration if the computed F-statistic exceeds the critical values.
4. Diagnostic Tests: To ensure the reliability of the model results:
    - Homoskedasticity Test: Checks for constant variance of the residuals.
    - Serial Correlation Test: Ensures residuals are not serially correlated.
    - Normality Test: Verifies that residuals follow a normal distribution.
    - CUSUM Test: Detects any structural changes in the model coefficients over the study period.
5. Error Correction Model (ECM) Estimation: Based on ARDL results, the ECM is used to capture short- and long-term dynamics. It also interprets the speed of adjustment toward equilibrium (CointEq(−1)) and assesses the impact of:
    - Renewable energy consumption as a percentage of electricity usage.

- Inflation rate.
- Population growth.
- Government consumption expenditure as a percentage of GDP.
- Net inflows of foreign direct investment as a percentage of GDP.

3.4. Ethics and Data Availability

In line with scientific transparency standards, all data used in this study are publicly accessible through the World Development Indicators (WDI) database of the World Bank. Researchers can access the same datasets to replicate the current analysis or extend it in future studies.

This research relies exclusively on publicly available macroeconomic data and does not involve any experiments on humans or animals. Therefore, no formal ethical approval is required.

3.5. Eco-Environmental Framework

To highlight the importance of integrating environmental considerations into energy economics, the literature suggests that incorporating CO_2 emission costs enhances the understanding of the true economic value of energy systems and improves sustainability assessment. Such approaches emphasize that renewable energy becomes more competitive when environmental externalities are included in economic evaluation frameworks.

However, due to data limitations and scope constraints, the present study does not empirically implement detailed eco-environmental indicators such as LCOE modification, CO_2 damage cost calculations, and payback time analysis. Nevertheless, their conceptual importance is acknowledged as a strong direction for future research in comprehensive energy–economic modeling and sustainable development studies.

This framework provides a foundation for future empirical integration of eco-economic optimization models in energy-growth studies.

4. Results

4.1. Summary of Stationarity Results

The stationarity of the variables used in this study was tested using the statistical software EViews 13, by applying the Augmented Dickey-Fuller (ADF) Test, with the aim of verifying whether the variables are stationary or non-stationary, i.e., whether they contain a unit root. The order of integration for each variable was also determined individually. After performing the test for all variables, the following results were obtained:

It is evident from **Table 1** and based on the results of the Augmented Dickey-Fuller (ADF) test that the time series for GDP growth (GDPG), government final consumption expenditure (GEXP), and inflation rate (INF) are stationary at the level, indicating the absence of a unit root. In contrast, the results show that the other variables—(REC), net inflows of foreign direct investment (FDI), and population growth (POP)—are non-stationary at level and contain a unit root, but they become stationary after taking the first difference, i.e., they are integrated of order one I(1). Since the variables included in the model are not all of the same integration order but are distributed between I(0) and I(1), this allows the use of the Autoregressive Distributed Lag (ARDL) methodology to examine both short- and long-term relationships among the variables.

Table 1. Summary of Augmented Dickey-Fuller Test Results for the Stationarity of the Study Variables Time Series for the Period (2004–2024).

Unit Root Test Results Table (ADF)							
Null Hypothesis: The Variable Has a Unit Root							
At Level							
		GDPG	**REC**	**GEXP**	**INF**	**FDI**	**POP**
With Constant & Trend	*t*-Statistic	−4.1432	−1.5516	−4.2334	−5.0609	−3.5456	−3.6043
	Prob.	0.0200	0.7714	0.0199	0.0051	0.0683	0.0566
		**	n0	**	***	*	*

Table 1. *Cont.*

Unit Root Test Results Table (ADF)							
Null Hypothesis: The Variable Has a Unit Root							
At First Difference							
		d (GDPG)	**d (REC)**	**d (GEXP)**	**d (INF)**	**d (FDI)**	**d (POP)**
With Constant & Trend	*t*-Statistic	−6.4174	−7.3340	−4.1628	−4.1800	−4.2536	−3.9903
	Prob.	0.0003 ***	0.0001 ***	0.0202 **	0.0196 **	0.0170 **	0.0323 **

Source: Prepared by the researcher using EViews 13.
Note:
a: (*) Significant at the 10%; (**) Significant at the 5%; (***) Significant at the 1% and (no) Not Significant.
b: Lag Length based on SIC.
c: Probability based on MacKinnon (1996) one-sided *p*-values.
This result is the out-put of program has developed by Dr. Imadeddin AlMosabbeh, College of Business and Economics, Qassim University-KSA.

Figure 2 presents the time-series evolution of GDP growth and renewable energy consumption in India over the period 2004–2024. It is observed that both variables exhibit fluctuating but relatively related long-term movements, particularly during periods of economic slowdown and recovery. Although the two variables are measured in different units, the graphical representation provides a visual indication of potential co-movement between economic growth and renewable energy expansion. This supports the subsequent econometric analysis conducted using the ARDL approach.

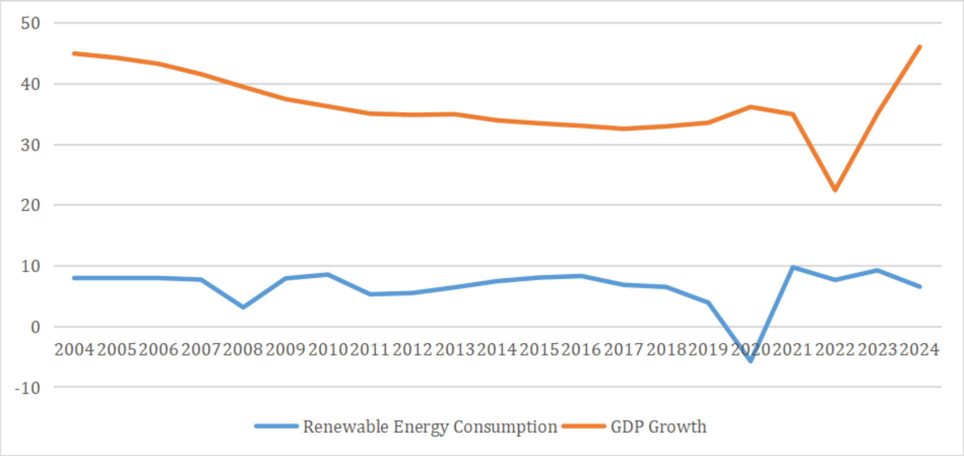

Figure 2. Time-Series Relationship between GDP Growth and Renewable Energy Consumption in India (2004–2024).

4.2. Estimation of the Study Model Using ARDL

The first step after testing the stationarity of the variables under study is to estimate the Autoregressive Distributed Lag (ARDL) model for unemployment rates in India. After performing the model estimation, the results are summarized in the following **Table 2**:

Table 2. Summary of ARDL Model Estimation Results for the Study Period (2004–2024).

Variable	**Coefficient**	**Std. Error**	***t*-Statistic**	**Prob.***
GDPG(−1)	−0.802582	0.246250	−3.259216	0.0099
DREC	−0.633064	0.214780	−2.947493	0.0163
DFDI	1.584548	2.099854	0.754599	0.4698
DFDI(−1)	2.073825	1.923325	1.078250	0.3090
GEXP	−4.279364	1.376248	−3.109443	0.0125
INF	−0.878056	0.367819	−2.387193	0.0407
INF(−1)	0.843508	0.380359	2.217661	0.0538
DPOP	74.16360	20.69223	3.584129	0.0059
DPOP(−1)	26.43355	18.85642	1.401833	0.1945
C	61.09196	15.68489	3.894955	0.0036

Table 2. *Cont.*

Variable	Coefficient	Std. Error	*t*-Statistic	Prob.*
R-squared	0.792792	Mean dependent var		6.328513
Adjusted R-squared	0.585584	S.D. dependent var		3.382506
S.E. of regression	2.177494	Akaike info criterion		4.699643
Sum squared resid	42.67330	Schwarz criterion		5.196716
Log likelihood	−34.64661	Hannan-Quinn criterion.		4.783768
F-statistic	3.826068	Durbin-Watson stat		2.169967
Prob(F-statistic)	0.029190			
Dependent Variable: GDPG				
Method: ARDL				
Date: 03/15/26 Time: 04:10				
Sample (adjusted): 2006 2024				
Included observations: 19 after adjustments				
Maximum dependent lags: 1 (Automatic selection)				
Model selection method: Akaike information criterion (AIC)				
Dynamic regressors (1 lag, automatic): DREC DFDI GEXP INF DPOP				
Fixed regressors: C				
Number of models evalulated: 32				
Selected Model: ARDL(1, 0, 1, 0, 1, 1)				

Source: Prepared by the researcher using EViews 13.

Note: *p*-values and any subsequent tests do not account for model selection. Difference in Renewable Energy Consumption (DREC).

It can be observed from **Table 2** above the following points:

The results of the ARDL model estimation.

It can be observed from **Table 2** that the ARDL model estimation results indicate a relatively strong explanatory power, with an R-squared value of 0.79. This suggests that approximately 79% of the variation in GDP growth (GDPG) is explained by the independent variables included in the model, while the remaining 21% is attributed to the error term.

In addition, the model is statistically significant at the 5% level, as shown by the F-statistic value of 3.826068 (Prob. = 0.029190). This indicates that the joint effect of the explanatory variables is statistically significant, leading to the rejection of the null hypothesis that all coefficients are equal to zero.

Furthermore, the Durbin–Watson statistic value of 2.16 is close to 2, suggesting that the model does not suffer from autocorrelation in the residuals, which supports the reliability of the estimated results.

Finally, based on the Akaike Information Criterion (AIC), the optimal lag structure selected for the model is ARDL(1, 0, 1, 0, 1, 1), which provides the best balance between model fit and parsimony.

These results provide important implications for policymakers and suggest that future research could extend the model by incorporating additional macroeconomic or environmental variables to further improve the robustness of the findings.

4.3. Bounds Test

The next step is to test for the existence of a long-run equilibrium relationship (cointegration) among the variables using the Bounds Test, as shown in the following **Table 3**:

Table 3. Bounds Test for the Estimated ARDL Model.

F-Bounds Test		Null Hypothesis: No Levels Relationship		
Test Statistic	**Value**	**Signif.**	**I(0)**	**I(1)**
			Asymptotic: n = 1000	
F-statistic	10.18366	10%	2.08	3
K	5	5%	2.39	3.38
		2.5%	2.7	3.73
		1%	3.06	4.15
Actual Sample Size	19		Finite Sample: n = 35	
		10%	2.331	3.417
		5%	2.804	4.013
		1%	3.9	5.419
			Finite Sample: n=30	
		10%	2.407	3.517
		5%	2.91	4.193
		1%	4.134	5.761

Source: Prepared by the researcher using EViews 13.

It is evident from **Table 3**, which presents the results of the Bounds test, that the calculated F-statistic is 10.18366. This value is higher than both the lower bound critical value (2.08) and the upper bound critical value (3.00) at the 10% significance level. Therefore, the null hypothesis of no long-run relationship among the variables is rejected.

This result confirms the existence of a long-run cointegration relationship between economic growth and the explanatory variables during the period 2004–2024. It implies that the variables move together in the long run, indicating a stable equilibrium relationship within the ARDL framework.

From an economic perspective, this finding supports the view that REC and other macroeconomic factors have a sustained impact on economic growth in India. The existence of cointegration also justifies the estimation of both long-run and short-run dynamics in the subsequent ARDL model.

These results provide important implications for policymakers, suggesting that long-term economic planning should consider the joint behavior of energy and macroeconomic variables. Future research may extend the analysis by incorporating additional structural or environmental factors to further validate the robustness of the long-run relationship.

4.4. Conducting Diagnostic Tests

After estimating the model parameters, it is necessary to assess the efficiency and reliability of the estimated model by performing a set of standard diagnostic tests to evaluate its quality, as follows:

- Homoskedasticity Test

It can be observed from **Table 4** that the model does not suffer from heteroskedasticity, as the statistical indicators are not significant, indicating that the residuals have constant variance. The probability value associated with the F-test is Prob. F = 0.3111, which is greater than the significance level of 0.05. Therefore, the null hypothesis of homoskedasticity in the residuals is accepted.

Table 4. Breusch-Pagan-Godfrey Test.

Heteroskedasticity Test: Breusch-Pagan-Godfrey			
Null Hypothesis: Homoskedasticity			
F-statistic	1.402843	Prob. F(9,9)	0.3111
Obs*R-squared	11.09270	Prob. Chi-Square(9)	0.2694
Scaled explained SS	2.460217	Prob. Chi-Square(9)	0.9819

Source: Prepared by the researcher using EViews 13.
Obs*R-squared refers to the number of observations multiplied by R-squared and is part of the test statistic, not a significance indicator.

- Serial Correlation Test of Residuals

It can be observed from **Table 5** that the model does not suffer from serial correlation in the residuals. The statistical indicators were not significant, with the probability associated with the F-test equal to Prob. F = 0.6903, which is above the accepted significance level of 0.05. This indicates that the null hypothesis of no serial correlation is accepted, confirming that the residuals are independent over time.

Table 5. LM Test.

Breusch-Godfrey Serial Correlation LM Test:			
Null Hypothesis: No Serial Correlation at up to 2 lags			
F-statistic	0.390910	Prob. F(2,7)	0.6903
Obs*R-squared	1.908883	Prob. Chi-Square(2)	0.3850

Source: Prepared by the researcher using EViews 13.
Obs*R-squared refers to the number of observations multiplied by R-squared and is part of the test statistic, not a significance indicator.

- Normality Test

Figure 3 below presents the results of the normality test for the residuals.

The Jarque–Bera test was used to examine whether the residuals follow a normal distribution. The resulting *p*-value was 0.995365, which is greater than 0.05. This indicates that there is no evidence to reject the normality assumption, and therefore the null hypothesis that the residuals are normally distributed is accepted.

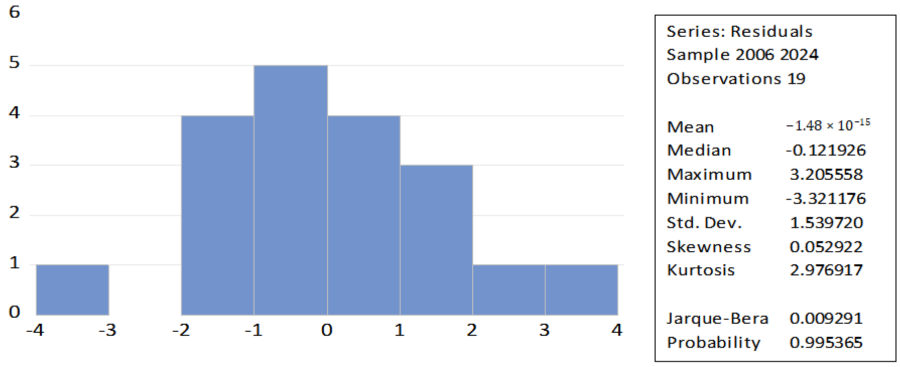

Figure 3. The results of the normality test for the residuals.

- Structural Stability Test of Model Parameters

To assess the structural stability of the estimated model, the CUSUM test was applied, as shown in **Figure 4** below.

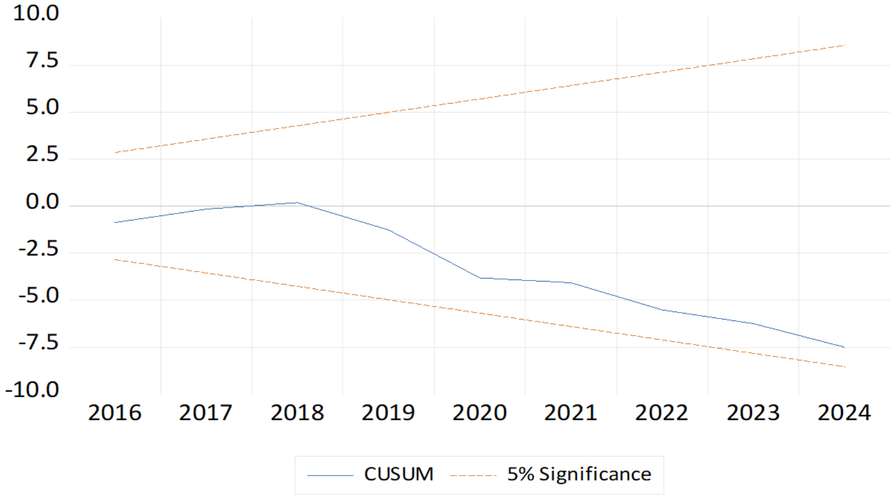

Figure 4. Structural stability of the estimated model using CUSUM.

Figure 4 presents the structural stability of the estimated model using the CUSUM test. The results show that the CUSUM statistic (blue line) remains entirely within the 5% significance confidence bounds (dashed lines) throughout the study period. This indicates that there are no structural breaks in the model, confirming its stability over time. Accordingly, the model exhibits a high degree of parameter stability, which strengthens the reliability and robustness of the estimated results.

4.5. Estimation of Short- and Long-Run Parameters and Error Correction Term

In light of the diagnostic tests, which confirmed the stability of the estimated model and the existence of a long-run equilibrium relationship among the variables, the next step is to estimate the short- and long-run coefficients using the Error Correction Model (ECM) within the framework of the Autoregressive Distributed Lag (ARDL) methodology, as shown in **Table 6.**

Based on the results of the Error Correction Model (ECM) derived from the ARDL model, it is evident that the model possesses a high explanatory power, with an R-squared value of approximately 0.89. This indicates that about 89% of the variations in GDP growth are explained by the independent variables included in the model.

The error correction term (CointEq(−1)) was estimated at −1.802582, which is negative and highly significant at the 1% level ($p = 0.0000$). This implies that any deviation of GDP growth from its long-run equilibrium is corrected within approximately one year, reflecting a moderate speed of adjustment toward equilibrium after a shock.

Table 6. The results of the Error Correction Model estimation.

ECM Regression

Case 2: Restricted Constant and No Trend

Variable	**Coefficient**	**Std. Error**	***t*-Statistic**	**Prob.**
D(DFDI)	1.584548	0.818977	1.934790	0.0850
D(INF)	−0.878056	0.242474	−3.621237	0.0056
D(DPOP)	74.16360	10.20688	7.266042	0.0000
CointEq(−1)*	−1.802582	0.165375	−10.89997	0.0000
R-squared	0.896558	Mean dependent var		−0.075193
Adjusted R-squared	0.875870	S.D. dependent var		4.787337
S.E. of regression	1.686679	Akaike info criterion		4.068064
Sum squared resid	42.67330	Schwarz criterion		4.266893
Log likelihood	−34.64661	Hannan-Quinn criterion.		4.101714
Durbin-Watson stat	2.169967			
ARDL Error Correction Regression				
Dependent Variable: D(GDPG)				
Selected Model: ARDL(1, 0, 1, 0, 1, 1)				
Case 2: Restricted Constant and No Trend				
Date: 03/15/26 Time: 04:27				
Sample: 2004 2024				
Included observations: 19				

Source: Prepared by the researcher using EViews 13.
Note: * *p*-value incompatible with *t*-Bounds distribution.

The results also show that inflation and population growth are significant determinants of short-run GDP growth, as indicated by their *p*-values = 0.0000, confirming the statistical significance of these relationships. Economically, the negative coefficient of inflation suggests an inverse relationship between inflation and GDP growth: higher inflation reduces individuals' purchasing power and increases production costs for firms, which constrains consumption and investment, ultimately slowing economic activity and short-run GDP growth.

Conversely, the positive and significant coefficient of population growth indicates a direct relationship with GDP growth. An increasing population can expand the labor force and raise aggregate demand for goods and services, stimulating economic activity and enhancing production. Additionally, population growth can enlarge the domestic market and encourage investment and production expansion, which positively affects short-run GDP growth.

The long-run results of the ARDL model are reported in **Table 7**.

Table 7. Long-Run Relationship Results.

Conditional Error Correction Regression

Variable	**Coefficient**	**Std. Error**	***t*-Statistic**	**Prob.**
C	61.09196	15.68489	3.894955	0.0036
GDPG(−1)*	−1.802582	0.246250	−7.320132	0.0000
DREC**	−0.633064	0.214780	−2.947493	0.0163
DFDI(−1)	3.658372	3.440722	1.063257	0.3154
GEXP**	−4.279364	1.376248	−3.109443	0.0125
INF(−1)	−0.034547	0.297193	−0.116246	0.9100
DPOP(−1)	100.5971	32.91606	3.056172	0.0137
D(DFDI)	1.584548	2.099854	0.754599	0.4698
D(INF)	−0.878056	0.367819	−2.387193	0.0407
D(DPOP)	74.16360	20.69223	3.584129	0.0059
ARDL Long Run Form and Bounds Test				
Dependent Variable: D(GDPG)				
Selected Model: ARDL(1, 0, 1, 0, 1, 1)				
Case 2: Restricted Constant and No Trend				
Date: 03/15/26 Time: 04:41				
Sample: 2004 2024				
Included observations: 19				

Source: Prepared by the researcher using EViews 13.
Note: * *p*-value incompatible with t-Bounds distribution.
** Variable interpreted as Z = Z(−1) + D(Z).

From **Table 7**, the following observations can be made regarding the long-run results of the ARDL model:

- Difference in Renewable Energy Consumption (DREC) exhibits a negative and significant impact on long-run GDP growth. This can be explained by the fact that transitioning to renewable energy in India requires substantial investments in infrastructure and technology, such as constructing solar and wind power plants and developing electricity transmission networks. Allocating a significant portion of resources to these investments may reduce the resources available for other productive sectors in the long run, especially during the early stages of the energy transition, which could temporarily suppress economic growth.

- Government consumption expenditure (GEXP) also shows a negative and significant effect on long-run GDP growth. This may be attributed to the fact that a substantial portion of government spending in India is directed toward current expenditures and social support programs. Such allocations might limit the positive impact of public spending on enhancing the economy's productive capacity, particularly if not accompanied by sufficient investments in infrastructure and productive sectors.
- Foreign direct investment (FDI) exhibits an insignificant effect on long-run GDP growth. This may reflect that the impact of foreign investment in India largely depends on the sectors in which it is directed. FDI might be concentrated in specific service or technology sectors without extending widely to other productive sectors, thereby limiting its direct long-term influence on GDP growth.
- Inflation rate (INF) also shows an insignificant effect on long-run GDP growth, indicating that the Indian economy can relatively adapt to changes in the general price level over the long term. This adaptability is partly due to the monetary policies implemented by the Reserve Bank of India to maintain price stability, which mitigates the long-term impact of inflation on economic growth.
- Population growth rate (DPOP) demonstrates a positive and significant effect on long-run GDP growth. India, being one of the most populous countries, benefits from an expanding domestic market and increasing aggregate demand for goods and services. A larger labor force supports productive activity, and if this population growth is effectively harnessed through education, training, and job creation, it can become a key driver of long-term economic growth.

5. Discussion

The results of this study provide meaningful empirical evidence on the relationship between renewable energy consumption (REC) and economic growth in India within the framework of the Energy–Growth Nexus. The findings reveal the existence of a long-run equilibrium relationship among the variables, which is consistent with several previous empirical studies that confirm the existence of a structural linkage between energy use and economic performance [1,3,14].

One of the key findings is the presence of a negative and statistically significant effect of REC on economic growth in the long run. This result differs from studies such Bhattacharya et al. [15], which report a positive impact of renewable energy on economic growth. This divergence may be explained by the transitional nature of renewable energy adoption in emerging economies like India, where significant investment costs in infrastructure and technology may temporarily constrain economic growth.

From a theoretical standpoint, this result does not fully support the Growth Hypothesis of the Energy–Growth Nexus. Instead, it appears to be more consistent with the Conservation Hypothesis, suggesting that energy consumption and economic growth may not always move in the same direction in developing economies.

Regarding government consumption, the results indicate a negative and significant long-run effect on economic growth. This finding is consistent with Keynesian theory, which argues that the impact of government spending depends on its composition. In particular, it supports previous studies suggesting that non-productive public expenditure may have limited or even adverse effects on long-term growth.

In the case of foreign direct investment (FDI), the findings show no statistically significant long-run impact on economic growth. This result is in line with studies that argue that the growth effects of FDI depend on absorptive capacity, institutional quality, and the sectoral distribution of investment.

On the other hand, population growth is found to have a positive and statistically significant effect on economic growth in both the short and long run. This result supports endogenous growth theory and is consistent with studies emphasizing the role of labor force expansion and human capital accumulation in driving economic development.

As for inflation, the results indicate a negative short-run impact on economic growth, which is consistent with conventional macroeconomic theory. However, its insignificance in the long run aligns with studies suggesting that economies may adjust over time to inflationary pressures through policy interventions and structural adjustments.

Overall, these findings demonstrate that the relationship between renewable energy and economic growth in India is complex and cannot be explained by a single theoretical framework. Instead, it reflects mixed dynamics within the Energy–Growth Nexus literature, where both positive and negative effects have been reported depending on country context, methodology, and time period.

These results highlight the importance of designing integrated energy and macroeconomic policies that balance the short-term adjustment costs of renewable energy transition with long-term sustainability goals. Future research could further explore sector-specific effects, regional disparities within India, and the role of technological innovation in strengthening the positive impact of renewable energy on economic growth.

6. Conclusions

This study investigated the relationship between REC and economic growth in India over the period 2004–2024 using the ARDL modeling approach. The findings confirm the existence of a long-run equilibrium relationship among the variables, reinforcing the relevance of the Energy–Growth Nexus in the Indian context.

The empirical results indicate that REC has a negative and significant effect on economic growth in the long run, reflecting the economic costs associated with the transition toward cleaner energy sources, particularly in the early stages. In addition, government consumption was found to negatively affect growth, while population growth emerged as a positive and significant contributor. Meanwhile, foreign direct investment and inflation did not show a significant long-term impact.

This study contributes to the existing literature by providing updated empirical evidence based on recent data and robust econometric techniques. It offers valuable insights for policymakers, particularly in emerging economies undergoing structural transformation.

Based on the findings, several policy implications can be drawn. These include the need to enhance the efficiency of investments in renewable energy, reallocate government spending toward productive sectors, strengthen the institutional environment to better leverage FDI, and invest in human capital to maximize the benefits of population growth.

In conclusion, achieving a balance between economic growth and environmental sustainability requires well-coordinated policies that take into account the structural characteristics of the economy. Further research is encouraged to deepen understanding of this relationship, particularly in relation to innovation and sectoral development.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

All data used in this study were obtained from reputable and publicly accessible sources, namely the World Bank's World Development Indicators (WDI) database and YCharts (India Central Government Final Consumption Expenditure as a Percentage of GDP.

Conflicts of Interest

The author declares no conflict of interest.

AI Use Statement

During the preparation of this work, the author used ChatGPT to assist with spelling, translation, and organizing the written content. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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