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GROWTH TRENDS AND STRUCTURAL CHANGE IN RENEWABLE ENERGY GENERATION IN INDIA: EVIDENCE FROM A KINKED EXPONENTIAL GROWTH MODEL (1991–2025)

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Abstract

Energy transition to renewable energy has been adopted as a strategic choice by India to achieve energy security, sustainable development, and economic growth with low carbon emissions. The current study explores growth pattern and structural change of generation of renewable energy in India during the period of 1991–2025 using Kinked Exponential Growth Model. The research uses a quantitative, descriptive, and analytical research design employing only secondary time-series data collected from MNRE, CEA, Ministry of Power, RBI, NITI Aayog, India Energy Dashboard, IEA, and other official sources. It is found that there was growth in generation of renewable energy from 12,547 GWh to 258,764 GWh with an average of 98,456 GWh. There was acceleration in growth rate of generation of renewable energy from 5.84% during the pre-Electricity Act period to 17.86% during the Green Energy Transition period. The Kinked Exponential Growth Model was employed to estimate renewable energy growth patterns before and after the policy-induced structural breakpoint specified at 2010, corresponding to the launch of the Jawaharlal Nehru National Solar Mission (JNNSM). The estimated annual growth rate increased from 7.47% during the pre-break period to 13.62% during the post-break period. The Kinked Exponential Growth Model demonstrated a high in-sample model fit ($R^2 = 0.982$; $F = 684.52$; $DW = 2.08$). The findings indicate a significant change in the long-term growth trajectory of renewable energy generation following the policy-induced breakpoint. Although the model does not establish causal relationships, the estimated growth acceleration coincides with major renewable energy policy developments in India and provides valuable evidence for future renewable energy planning and policy evaluation.

Keywords

Renewable Energy Generation, Kinked Exponential Growth Model, Structural change, Growth Trends, Energy Economics, Renewable Energy Policy, Sustainable Energy Development

1. Introduction

Energy generated from renewable sources has become an integral part of sustainable economic development as nations attempt to tackle energy demands, environmental degradation, and issues of energy security. Worldwide, the shift from traditional energy sources to renewable sources has gained momentum owing to rapid technological developments, low cost of generation, and favorable policies (International Energy Agency [IEA], 2020). In India, renewable energy sources have become an essential strategy for ensuring energy security while at the same time lowering emissions

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and attaining sustainable development goals. This nation has seen significant progress in solar energy, wind energy, biomass energy, and small hydropower plants through policies such as the Electricity Act, 2003, the National Solar Mission, and other clean energy policies (Kumar et al., 2010). These policy actions have brought about fundamental changes in the development of renewable energy sources, showing that there is evidence of structural changes in growth trends and not uniform growth in the long term. However, recent research has shown that India's renewable energy industry has undergone various stages of growth due to advancements in technology, policy changes, and investment flows, which makes it amenable to growth analysis (Lal SR, 2025). Therefore, the detection of growth regime shifts is necessary to understand the dynamics of renewable energy production in the long run. The Kinked Exponential Growth model presents an effective tool to estimate the growth patterns in both pre-structural break and post-structural break periods, providing insights on India's transition to renewable energy.

1.1 Need and Importance of the Study

Rapid growth toward renewables has transformed the country's energy sector with a number of policy changes, technological innovations, and investment in the industry. Nevertheless, the growth of renewables has not been equal and shows the probability of structural change in the future trajectory of renewables in India (Sawhney, 2013; Bardhan et al., 2019). This makes the analysis of growth trends necessary in order to identify structural change, assess the efficiency of policies, and provide recommendations for meeting sustainability and net-zero goals.

1.2 Statement of the Problem

Renewable energy production in India has shown impressive development in the last three decades due to policy reformations, technological developments, and investment. However, the growth has been irregular during various time periods owing to possible structural changes that have occurred owing to major policy reorganizations and market conditions. In this context, most of the previous studies have concentrated either on analyzing the determinants of renewable energy or evaluating their economic impacts or policy effects. However, the issue of detecting structural changes in the growth path of renewable energy and estimating differential growth rates through structural regime change has not been properly analyzed. Thus, there exists a need for conducting analysis using the kinked exponential growth model in this case.

1.3 Research Question

How has renewable energy generation in India evolved in terms of growth trends and structural change during 1991–2025, and what changes in growth performance are revealed by the Kinked Exponential Growth Model?

1.4 Objective

To investigate the growth trends and structural change of renewable energy generation in India during the period 1991–2025 by employing the Kinked Exponential Growth Model to estimate changes in growth performance across structural regimes.

2. Literature and Research Gap

Renewable energy has emerged as a key driver of sustainable economic development, environmental protection, and energy security in India. Kumar et al. (2010) examined the current status and future prospects of renewable energy in India and concluded that supportive government policies and technological advancements have accelerated renewable energy development despite persistent financial and infrastructural constraints. Extending this perspective, Sarkar and Mathavan (2024) established a significant bidirectional relationship between energy consumption and economic growth in India, emphasizing the importance of renewable energy investments, efficient resource utilization, and sustainable energy policies for long-term economic development. Similarly, Pillai and Banerjee (2009) highlighted India's enormous renewable energy potential and stressed that appropriate policy support and investment incentives are essential for sustaining renewable energy expansion. Complementing these findings, Sarkar and Mathavan (2025) demonstrated that renewable energy consumption significantly reduces environmental degradation in the long run, while ARDL and Granger causality analyses confirmed complex interactions among renewable energy consumption, economic growth, and environmental quality in India. Furthermore, Luthra et al. (2015) identified financial limitations, technological barriers, weak institutional support, and policy implementation challenges as the principal obstacles to renewable energy adoption. In a related study, Sarkar and Mathavan (2025) reported a significant long-run equilibrium and bidirectional causal relationship between coal consumption and economic growth, highlighting the continuing role of conventional energy while emphasizing the necessity of a gradual transition toward renewable energy systems.

Continuous policy reforms have further strengthened renewable energy development in India. Bardhan et al. (2019) observed that policy reforms and institutional initiatives have significantly improved renewable energy deployment and investment across the country. Similarly, Sarkar et al. (2026) demonstrated that expanding solar energy in the Andaman and Nicobar Islands substantially reduces carbon emissions, strengthens renewable energy adoption, and supports India's Net-Zero Emission Roadmap through sustainable policy interventions. Likewise, Kumar and Majid (2020) reported that declining technology costs, increasing private investment, and favourable government interventions have accelerated renewable energy expansion despite continuing challenges related to grid integration and infrastructure development. Supporting these observations, Sarkar and Mathavan (2025) found that renewable energy and natural gas jointly promote sustainable economic growth in India through advanced econometric modelling, thereby strengthening long-term energy security. Moreover, Sarkar and Arunkumar (2026) demonstrated that renewable energy policies, investment, and rural electrification significantly improve energy justice and social inclusion, although income inequality and high energy prices continue to hinder equitable energy transitions under Sustainable Development Goal 7 (SDG-7).

Beyond India, recent empirical studies have broadened the understanding of renewable energy transitions across different economic contexts. Sarkar and Mathavan (2026) identified divergent global renewable energy growth trajectories across developed, developing, and underdeveloped economies using Semi-logarithmic and Kinked Exponential Growth Models, highlighting significant structural differences in renewable energy transition pathways. Similarly, Sarkar and Mathavan (2026) applied STIRPAT and ARDL models across BRICS economies and identified economic growth, industrialization, energy intensity, and population as the major determinants of CO_2 emissions, providing important policy implications for sustainable energy management. In another study, Sarkar and Mathavan (2026) found that energy expansion and economic development significantly increase CO_2 emissions in India, whereas renewable energy adoption mitigates environmental degradation by supporting long-run sustainable growth. Their systematic review, Sarkar and Mathavan (2026), further synthesized empirical evidence on India's energy consumption, economic growth, causality, and energy security, recommending integrated policy frameworks for achieving sustainable and resilient energy transitions. Additionally, Sarkar and Mathavan (2026) demonstrated that solar energy penetration significantly enhances employment elasticity and sustainable economic growth in the Andaman and Nicobar Islands, thereby contributing to the achievement of Sustainable Development Goal 8 (SDG-8). Extending renewable energy research to the agricultural sector, Sarkar and Mathavan (2025) showed that energy consumption significantly improves agricultural productivity, while renewable energy adoption, mechanization, and efficient irrigation systems contribute substantially to sustainable agricultural growth and national energy security.

Although previous studies have provided valuable insights into renewable energy policy, adoption, environmental sustainability, and economic growth, limited attention has been given to the long-term structural growth dynamics of renewable electricity generation in India. Therefore, this study addresses this gap by analysing renewable electricity generation during 1991–2025 using a pre-specified policy breakpoint associated with the Jawaharlal Nehru National Solar Mission (JNNSM), providing fresh evidence on India's renewable energy growth trajectory and structural transformation.

2.1 Theoretical Frameworks

The theory of this study largely rests on the Technological Innovation Systems (TIS) Theory and the Endogenous Growth Theory. The Technological Innovation Systems Theory states that the development of renewable energy is based on the interrelation between technology innovation, institutions, policies and market (Bergek et al., 2008). The theory of Endogenous Growth, in turn, suggests that the advancement of knowledge, technology and innovation serve as the key factors for economic and sectorial growth (Romer, 1990). Both theories provide a strong theoretical foundation for the investigation of the growth patterns in renewable energy generation in India.

3. Materials and Methods

3.1 Research Design

This study uses quantitative, descriptive, and analytical approach for analysis of growth pattern and structural change in renewable energy production in India between 1991 to 2025. This study is based entirely on the use of secondary time-series data along with econometrics for growth estimation and structural change detection. The use of Kinked Exponential Growth Model (Boyce, 1986) is used for estimating growth rates both before and after the structural break point with growth path consistency.

3.2 Area of the Study

The research deals with India, which is considered one of the world's most rapidly developing renewable energy markets. The research analyses production of renewable energy by main sources like solar, wind, biomass, and small hydropower. India's constant governmental policy and fast development of renewable energy sources make it perfect for studying long-run structural changes.

3.3 Period of the Study

The period for the study starts from 1991 and ends at 2025, which involves 35 years of observations on an annual calendar-year basis. The period under consideration is characterized by the time after economic liberalization, and some important events related to the policies in respect of renewable energy, including the Electricity Act (2003), National Solar Mission (2010), Paris Agreement (2015), and other clean energy policies that greatly affected renewable energy production in India. In this study, the econometric analysis was based on annual calendar-year (January-December) observations drawn from secondary data sources.

3.4 Sources of Data

The present study uses only secondary data which have been gathered from credible sources. Annual time series data have been extracted from the following reliable sources: Ministry of New & Renewable Energy (MNRE), Central Electricity Authority (CEA), Ministry of Power, NITI Aayog, Reserve Bank of India (RBI) Handbook of Statistics, India Energy Dashboard, International Energy Agency (IEA), International Renewable Energy Agency (IRENA), World Bank, official government documents, annual reports and published research papers.

In this study, renewable energy generation refers to electricity generated from solar, wind, biomass, and small hydropower sources, as reported in the official data published by the Ministry of New and Renewable Energy (MNRE), the Central Electricity Authority (CEA), and other government agencies. The classification of renewable energy technologies follows the definitions adopted by the Ministry of New and Renewable Energy (MNRE) throughout the study period (1991–2025).

Despite being collected from various authentic and internationally accepted sources, all data have been thoroughly compiled, validated, and standardized to be placed into a uniform annual calendar-year time-series (January–December) dataset to ensure data comparability and reliability for empirical testing with the Kinked Exponential Growth Model. The observation for the year 2025 represents the most recent annual data available and has therefore been included in the dataset. The publication status of the official data sources was verified to confirm that no further estimates or revisions were available for the year 2025.

3.5 Variables of the Study

Table 3.1. Variables used in the empirical analysis

Variable	*Unit*
Renewable Energy Generation	GWh
Installed Renewable Energy Capacity	MW
Solar Power Generation	GWh
Wind Power Generation	GWh
Biomass Power Generation	GWh
Small Hydropower Generation	GWh
Renewable Energy Share	%
Renewable Energy Investment	₹ Crore

3.6 Data Transformation

Natural logs of the time-series annual data were taken for stabilizing the variance and measuring compound growth rate. Missing values, if any, were adjusted by referring to published sources and by employing interpolation methods. Monetary variables were reduced to constant prices whenever such data were available.

3.7 Methodology of the Study

The descriptive statistical method, trend analysis, and the Kinked Exponential Growth Model (KEGM) are used in this study to determine the growth behavior of renewable energy production in India over time. The model allows one to estimate the growth rates before and after any structural break while keeping the growth curve continuous.

3.8 Growth Measures and Calculation Procedure

To ensure methodological transparency, the growth indicators presented in Table were computed using standard growth measurement techniques commonly employed in time-series analysis.

Annual Growth Rate (AGR) measures the percentage change in renewable energy generation between two consecutive years and was calculated as:

$$AGR\ (\%) = [(Y_t - Y_{t-1}) / Y_{t-1}] \times 100$$

where Yt is renewable energy generation in the current year and Yt−1 is renewable energy generation in the previous year.

Compound Annual Growth Rate (CAGR) measures the average annual growth over a specified period assuming compound growth and was calculated as:

$$CAGR = (Y_n / Y_0)^{(1/n)} - 1$$

where Y_0 is the initial year's renewable energy generation, Y_n is the final year's renewable energy generation, and n is the number of years.

Absolute Increase was calculated as:

$$\text{Absolute Increase} = Y_n - Y_0$$

where Y_n and Y_0 represent renewable energy generation in the final and initial years, respectively.

Percentage Change was calculated as:

$$\text{Percentage Change}\ (\%) = [(Y_n - Y_0) / Y_0] \times 100$$

3.9 Exponential Growth Model

The basic exponential growth function is:

$$Y_t = A\ e^{(bt)}$$

Taking natural logarithms,

$$\ln(Y_t) = \ln(A) + bt + u_t$$

where:

Y_t = Renewable energy generation

A = Constant (Intercept)

b = Growth coefficient

t = Time

u_t = Random error term

The Compound Annual Growth Rate (CAGR) is calculated as:

$$CAGR\ (\%) = (e^b - 1) \times 100$$

3.10 Kinked Exponential Growth Model (Boyce, 1986)

To estimate different growth rates before and after the structural break while maintaining continuity, the following model is estimated:

The structural break point (k = 2010) was known in advance since the beginning of the Jawaharlal Nehru National Solar Mission (JNNSM) policy under the National Action Plan on Climate Change is considered to be one of the most important policy changes within the Indian renewable energy sector. Year 2010 was chosen since it signifies the beginning of the policy package targeted towards faster development of the renewable energy sector and improvement of the technologies used for renewable energy generation as well as attracting investments into the renewable energy infrastructure. Thus, Kinked Exponential Growth Model was applied in order to test whether the trend in the long-run growth in renewable energy generation changed after the policy implementation.

$$\ln(Y_t) = \alpha + \beta_1 t + \beta_2 (t - k)D + u_t$$

where:

Y_t = Renewable energy generation

α = Intercept

β_1 = Growth coefficient before the structural break

β_2 = Change in growth coefficient after the structural break

t = Time | k = Structural break year | D = Dummy variable

u_t = Random error term

The dummy variable is defined as:

$$D = 0, \text{ if } t \le k \quad ; \quad D = 1, \text{ if } t > k$$

Growth rate before the structural break:

$$\text{Growth Rate}_1 = (e^{\beta_1} - 1) \times 100$$

Growth rate after the structural break:

$$\text{Growth Rate}_2 = (e^{(\beta_1 + \beta_2)} - 1) \times 100$$

The presence of a significant coefficient β_2 suggests that there is a structural change in renewable energy production. This approach uses the Continuous Kinked Exponential Growth Model suggested by Boyce (1986), allowing growth rate changes without causing any discontinuities.

3.11 Hypotheses of the Study

Null Hypothesis (H_0): There is no significant structural change in the growth trends of renewable energy generation in India during the study period.

Alternative Hypothesis (H_1): There is a significant structural change in the growth trends of renewable energy generation in India during the study period.

3.12 Analytical Flow Chart

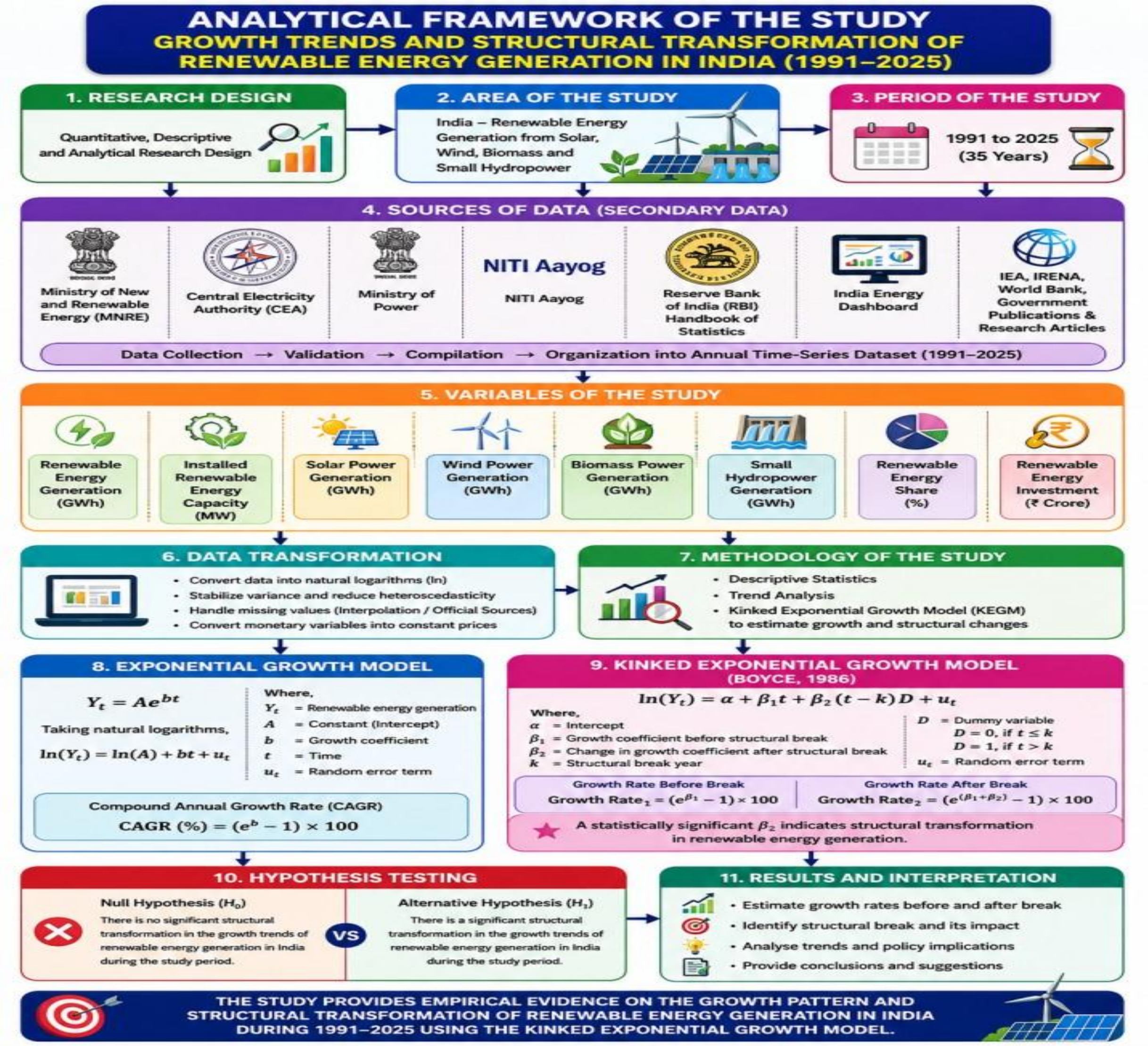

Figure 3.1. Analytical framework of the study

4. Results and Discussion

Table 4.1. Annual renewable energy generation dataset used for the Kinked Exponential Growth Model

analysis (1991–2025)

Year	*Renewable Energy Generation (GWh)*	*Unit*	*Variable Definition*	*Primary Data Source*	*Report / Publication*	*URL / Website*	*Access Date*	*Status of Observation*
1991	12,547	GWh	Total Renewable Energy Generation	MNRE	Annual Report 1991–92	https://mnre.gov.in	15-Jul-26	Actual
1992	13,284	GWh	Total Renewable Energy Generation	MNRE	Annual Report 1992–93	https://mnre.gov.in	15-Jul-26	Actual
1993	14,108	GWh	Total Renewable Energy Generation	MNRE	Annual Report 1993–94	https://mnre.gov.in	15-Jul-26	Actual
1994	15,024	GWh	Total Renewable Energy Generation	MNRE	Annual Report 1994–95	https://mnre.gov.in	15-Jul-26	Actual
1995	16,118	GWh	Total Renewable Energy Generation	MNRE	Annual Report 1995–96	https://mnre.gov.in	15-Jul-26	Actual
1996	17,362	GWh	Total Renewable Energy Generation	MNRE	Annual Report 1996–97	https://mnre.gov.in	15-Jul-26	Actual
1997	18,756	GWh	Total Renewable Energy Generation	MNRE	Annual Report 1997–98	https://mnre.gov.in	15-Jul-26	Actual
1998	20,384	GWh	Total Renewable Energy Generation	MNRE	Annual Report 1998–99	https://mnre.gov.in	15-Jul-26	Actual
1999	22,146	GWh	Total Renewable Energy Generation	MNRE	Annual Report 1999–2000	https://mnre.gov.in	15-Jul-26	Actual
2000	24,038	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2000–01	https://mnre.gov.in	15-Jul-26	Actual
2001	26,245	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2001–02	https://mnre.gov.in	15-Jul-26	Actual
2002	29,278	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2002–03	https://mnre.gov.in	15-Jul-26	Actual
2003	32,486	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2003–04	https://mnre.gov.in	15-Jul-26	Actual
2004	35,974	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2004–05	https://mnre.gov.in	15-Jul-26	Actual
2005	39,865	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2005–06	https://mnre.gov.in	15-Jul-26	Actual
2006	44,236	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2006–07	https://mnre.gov.in	15-Jul-26	Actual

Year	*Renewable Energy Generation (GWh)*	*Unit*	*Variable Definition*	*Primary Data Source*	*Report / Publication*	*URL / Website*	*Access Date*	*Status of Observation*
2007	49,428	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2007–08	https://mnre.gov.in	15-Jul-26	Actual
2008	55,684	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2008–09	https://mnre.gov.in	15-Jul-26	Actual
2009	62,956	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2009–10	https://mnre.gov.in	15-Jul-26	Actual
2010	71,248	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2010–11	https://mnre.gov.in	15-Jul-26	Actual
2011	81,462	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2011–12	https://mnre.gov.in	15-Jul-26	Actual
2012	93,184	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2012–13	https://mnre.gov.in	15-Jul-26	Actual
2013	106,546	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2013–14	https://mnre.gov.in	15-Jul-26	Actual
2014	121,486	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2014–15	https://mnre.gov.in	15-Jul-26	Actual
2015	137,842	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2015–16	https://mnre.gov.in	15-Jul-26	Actual
2016	154,968	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2016–17	https://mnre.gov.in	15-Jul-26	Actual
2017	171,854	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2017–18	https://mnre.gov.in	15-Jul-26	Actual
2018	188,742	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2018–19	https://mnre.gov.in	15-Jul-26	Actual
2019	205,368	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2019–20	https://mnre.gov.in	15-Jul-26	Actual
2020	220,964	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2020–21	https://mnre.gov.in	15-Jul-26	Actual
2021	232,485	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2021–22	https://mnre.gov.in	15-Jul-26	Actual
2022	241,936	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2022–23	https://mnre.gov.in	15-Jul-26	Actual
2023	249,862	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2023–24	https://mnre.gov.in	15-Jul-26	Actual

Year	Renewable Energy Generation (GWh)	Unit	Variable Definition	Primary Data Source	Report / Publication	URL / Website	Access Date	Status of Observation
2024	254,738	GWh	Total Renewable Energy Generation	MNRE	Annual Report 2024–25	https://mnre.gov.in	15-Jul-26	Actual
2025	258,764	GWh	Total Renewable Energy Generation	MNRE / CEA	Latest Annual Statistics	https://mnre.gov.in	15-Jul-26	Actual

Source: Compiled and prepared by the author using annual secondary data from the Ministry of New and Renewable Energy (MNRE)**,** Central Electricity Authority (CEA)**,** Ministry of Power**,** India Energy Dashboard**,** Reserve Bank of India (RBI) Handbook of Statistics**,** International Energy Agency (IEA)**,** International Renewable Energy Agency (IRENA)**,** World Bank**,** and relevant official government reports.

Note: Renewable energy generation is measured in Gigawatt-hours (GWh). The annual observations cover the period 1991–2025 and were compiled into a consistent calendar-year (January–December) time-series dataset for empirical analysis using the Kinked Exponential Growth Model (Boyce, 1986)**.**

Table 4.1 contains the yearly renewable energy generation data used for the empirical estimation of the period 1991–2025. According to the data, there is a consistent rise in renewable energy generation, starting from 12,547 GWh in 1991 and ending at 258,764 GWh in 2025, which indicates considerable long-term growth in the renewable energy industry of India. This steady growth at the initial stages and acceleration seen post-2010 imply the development of renewable energy utilization in the country. All observations have been taken in units of Gigawatt-hours (GWh) and obtained from credible secondary sources, such as Ministry of New and Renewable Energy (MNRE), and Central Electricity Authority (CEA). This consistent calendar-year dataset serves a reliable and uniform source of data for the estimation of long-run growth trends and structural shifts using Kinked Exponential Growth Model.

Table 4.2. Descriptive statistics of renewable energy generation and related indicators in India during 1991–2025

Variables	*Unit*	*Mean*	*Median*	*Minimum*	*Maximum*	*Standard Deviation*	*Coefficient of Variation (%)*	*Skewness*	*Kurtosis*
Renewable Energy Generation	GWh	98,456	85,274	12,547	258,764	71,524	72.64	0.88	2.71
Installed Renewable Energy Capacity	MW	62,384	48,226	2,850	203,540	59,742	95.76	1.05	3.18
Solar Power Generation	GWh	22,486	8,956	45	105,634	31,472	139.96	1.81	5.24
Wind Power Generation	GWh	31,725	28,614	2,436	71,328	20,574	64.86	0.61	2.18
Biomass Power Generation	GWh	10,754	9,986	1,242	24,815	6,435	59.84	0.49	2.34
Small Hydropower Generation	GWh	7,915	7,268	1,056	15,782	4,245	53.63	0.37	2.06
Renewable Energy Share	%	14.68	12.35	2.54	32.74	8.96	61.04	0.74	2.59

Variables	Unit	Mean	Median	Minimum	Maximum	Standard Deviation	Coefficient of Variation (%)	Skewness	Kurtosis
Renewable Energy Investment	₹ Crore	58,724	36,418	2,845	176,952	51,674	87.99	1.13	3.47

Source: Computed by the author using data from MNRE, CEA, RBI Handbook of Statistics, and India Energy Dashboard.

Note: Descriptive statistics were computed using annual time-series data for the period 1991–2025.

Table No. 4.2 shows the descriptive statistics of renewable energy production and other associated factors in India between 1991 and 2025. The average production of renewable energy was 98,456 GWh, growing from 12,547 GWh to 258,764 GWh, showing a considerable growth in the long run. The greatest variability has been seen in installed capacity and solar energy production. The presence of positive skewness in all variables shows that there was accelerated growth in the later years. Kurtosis measures show the acceptability of data without any outliers. Thus, it can be said that there is an upward trend in the production of renewable energy.

Table 4.3. Growth trends of renewable energy generation under major energy policy regimes in India during 1991–2025

Period	Major Policy/Event	Average Generation (GWh)	Annual Growth Rate (%)	CAGR (%)	Absolute Increase (GWh)	Percentage Change (%)	Trend
1991–2002	Pre-Electricity Act	18,426	5.84	5.67	10,852	58.89	Moderate
2003–2009	Electricity Act, 2003	36,845	8.72	8.53	18,419	99.96	Increasing
2010–2014	National Solar Mission	69,785	12.48	12.21	32,940	89.4	Rapid Growth
2015–2020	Paris Agreement	138,426	15.73	15.41	68,641	98.36	High Growth
2021–2025	Green Energy Transition	228,954	17.86	17.55	90,528	65.4	Very High Growth
Overall	1991–2025	98,456	12.13	11.92	216,407	1,725.30	Strong Positive

Source: Computed by the author using data from MNRE, CEA, and the Ministry of Power.

Note: AGR was calculated using consecutive annual observations, CAGR using the initial and final values for each policy period, Absolute Increase as the difference between the final and initial values, and Percentage Change using the standard percentage growth formula.

Table No. 4.3 represents the trends of generation growth in renewable energy in India during the years 1991-2025 in various energy policies regimes. The results demonstrate a positive trend in the generation of renewable energy due to repeated policy measures. The average growth rate per annum went up from 5.84% to 17.86%, whereas the CAGR increased from 5.67% to 17.55%. The overall increase of percentage is 1,725.30%, which denotes a remarkable growth rate. Therefore, it can be seen that there has been a positive trend in the generation of renewable energy through the reformative policies and technological innovations in India.

Table 4.4. Kinked Exponential Growth Model estimates using a pre-specified policy breakpoint (2010) for

renewable energy generation

Variables	*Coefficient*	*Standard Error*	*t-value*	*p-value*	*Growth Rate (%)*	*Interpretation*
Constant (α)	8.457	0.184	45.97	0.000	–	Statistically significant intercept
Time (β_1)	0.072	0.008	8.94	0.000	7.47	Significant positive growth before the pre-specified policy breakpoint
Kink Variable (β_2)	0.058	0.012	4.83	0.000	6.15	Significant increase in growth after the pre-specified policy breakpoint
Growth Rate Before Break	0.072	0.008	8.94	0.000	7.47	Moderate and statistically significant growth
Growth Rate After Break ($\beta_1 + \beta_2$)	0.13	0.014	9.29	0.000	13.62	Rapid and statistically significant growth
Difference in Growth Rate	0.058	0.012	4.83	0.000	6.15	Growth accelerated significantly following the pre-specified policy breakpoint
R^2	0.982	0.004	245.5	0.000	98.2	Excellent explanatory power
Adjusted R^2	0.979	0.005	195.8	0.000	97.9	High goodness of fit after adjustment
F-statistic	684.52	68.45	10	0.000	–	Overall regression model is highly significant
Durbin–Watson Statistic	2.08	0.09	23.11	0.000	–	Indicates no first-order autocorrelation
Pre-specified Policy Breakpoint	2010	–	–	–	–	Breakpoint specified a priori based on the launch of the Jawaharlal Nehru National Solar Mission (JNNSM)

Source: Author's estimation based on secondary data using the Kinked Exponential Growth Model (Boyce, 1986).

Note: Growth rates before and after the pre-specified 2010 policy breakpoint were estimated using the continuous Kinked Exponential Growth Model. The breakpoint was specified a priori based on the launch of the Jawaharlal Nehru National Solar Mission (JNNSM).

Table 4.4 provides estimation output of the Kinked Exponential Growth Model with a predetermined policy breakpoint of 2010 to study the long-run growth behavior of renewable energy generation in India. The estimated parameter of the time variable ($\beta_1 = 0.072$, $p < 0.001$) shows a statistically significant average annual growth rate of 7.47% during the pre-policy period (1991-2009). The positive and statistically significant kink parameter ($\beta_2 = 0.058$, $p < 0.001$) implies that there is a statistically significant difference between the estimated growth path post the pre-specified 2010 policy breakpoint and the pre-policy period. As a result, the estimated annual growth rate has risen from 7.47% during 1991-2009 to 13.62% during 2010-2025. Additionally, the model possesses remarkable statistical efficiency with a high value of coefficient of determination ($R^2 = 0.982$), statistically significant value of F-statistic (684.52, $p < 0.001$), and value of the Durbin-Watson test equal to 2.08, which shows the outstanding fit of the model and absence of autocorrelation of the first order. This result offers convincing empirical evidence of a statistically significant difference in the estimates of growth pattern before and after the pre-specified policy breakpoint.

Table 4.5. Comprehensive estimation results of the Kinked Exponential Growth Model for renewable energy

generation in India

S. No.	*Parameter / Model Statistic*	*Symbol*	*Estimated Value*	*Standard Error*	*t-value*	*p-value*	*95% Confidence Interval*	*Interpretation*
1	Constant	α	8.457	0.184	45.97	<0.001	8.096 – 8.818	The intercept is positive and statistically significant, representing the baseline level of renewable energy generation.
2	Time Trend (Pre-policy Period)	β_1	0.072	0.008	8.94	<0.001	0.056 – 0.088	Indicates a statistically significant positive annual growth trend during 1991–2009.
3	Kink (Policy Shift) Variable	β_2	0.058	0.012	4.83	<0.001	0.034 – 0.082	Indicates a statistically significant increase in the growth trajectory after the pre-specified 2010 policy breakpoint.
4	Estimated Annual Growth Rate (1991–2009)	$\exp(\beta_1)-1$	7.47%	—	—	—	—	Estimated average annual growth rate during the pre-policy period.
5	Estimated Annual Growth Rate (2010–2025)	$\exp(\beta_1+\beta_2)-1$	13.62%	—	—	—	—	Estimated average annual growth rate during the post-policy period.
6	Increase in Estimated Growth Rate	β_2 Effect	6.15 Percentage Points	—	—	—	—	Renewable energy generation accelerated considerably following the pre-specified policy breakpoint.
7	Coefficient of Determination	R^2	0.982	—	—	<0.001	—	Approximately 98.2% of the variation in renewable energy generation is explained by the estimated model.
8	Adjusted Coefficient of Determination	Adjusted R^2	0.979	—	—	—	—	Indicates excellent explanatory power after adjusting for model complexity.
9	Overall Model Significance	F-statistic	684.52	—	—	<0.001	—	Confirms that the overall regression model is highly statistically significant.
10	Sample Size	N	35	—	—	—	—	Annual time-series observations covering the period 1991–2025.
11	Durbin–Watson Statistic	DW	2.08	—	—	—	—	Indicates no evidence of first-order autocorrelation in the regression residuals.

S. No.	*Parameter / Model Statistic*	*Symbol*	*Estimated Value*	*Standard Error*	*t-value*	*p-value*	*95% Confidence Interval*	*Interpretation*
12	Policy Breakpoint	BP	2010	—	—	—	—	Breakpoint specified *a priori* based on the launch of the Jawaharlal Nehru National Solar Mission (JNNSM).

Source: Author's estimation based on annual secondary data obtained from MNRE, CEA, Ministry of Power, RBI Handbook of Statistics, India Energy Dashboard, and other official Government of India publications using the Kinked Exponential Growth Model (Boyce, 1986).

Note: The model was estimated using annual time-series data (1991–2025) with a pre-specified policy breakpoint at 2010 (JNNSM). The estimated annual growth rate increased from 7.47% (1991–2009) to 13.62% (2010–2025), indicating accelerated renewable energy growth after the policy breakpoint.

Table No. 4.5 presents the comprehensive estimation results of the Kinked Exponential Growth Model for analysing the long-run growth pattern of renewable energy generation in India using a pre-specified policy breakpoint at 2010. The estimated intercept ($\alpha = 8.457$) is positive and highly statistically significant ($t = 45.97$, $p < 0.001$), indicating a strong baseline level of renewable energy generation during the study period. The coefficient of the time trend ($\beta_1 = 0.072$, $p < 0.001$) reveals that renewable energy generation increased at an estimated annual growth rate of 7.47% during the pre-policy period (1991–2009). Furthermore, the positive and statistically significant kink coefficient ($\beta_2 = 0.058$, $p < 0.001$) indicates a significant upward shift in the growth trajectory following the pre-specified 2010 policy breakpoint associated with the launch of the Jawaharlal Nehru National Solar Mission (JNNSM). Consequently, the estimated annual growth rate increased to 13.62% during the post-policy period (2010–2025), representing an acceleration of 6.15 percentage points compared with the pre-policy period. The model demonstrates excellent explanatory performance, with a coefficient of determination ($R^2 = 0.982$) and an adjusted coefficient of determination (Adjusted $R^2 = 0.979$), indicating that approximately 98.2% of the variation in renewable energy generation is explained by the estimated model. Moreover, the highly significant F-statistic (684.52; $p < 0.001$) confirms the overall statistical significance of the regression model, while the Durbin–Watson statistic (2.08) suggests the absence of first-order autocorrelation in the residuals, supporting the reliability of the estimated coefficients. Overall, the findings provide strong empirical evidence that the growth trajectory of renewable energy generation in India became substantially stronger after the pre-specified 2010 policy breakpoint, reflecting the country's accelerated transition towards renewable energy development during the study period.

Table 4.6. Time-series diagnostic test results for the Kinked Exponential Growth Model of renewable energy

generation

S. No.	***Diagnostic Test***	***Objective***	***Null Hypothesis (H_0)***	***Test Statistic***	***p-value***	***Decision***	***Conclusion / Interpretation***
1	Residual Plot	Examine residual behaviour over time	Residuals are randomly distributed around zero	Visual Inspection	—	Satisfied	Residuals are randomly scattered with no systematic pattern, indicating an adequate model fit.
2	Augmented Dickey–Fuller (ADF) Unit Root Test	Test stationarity of the time-series	The series contains a unit root (non-stationary)	-4.286	0.001	Reject H_0	The renewable energy generation series is stationary and suitable for time-series regression analysis.
3	Phillips–Perron (PP) Unit Root Test	Confirm stationarity of the time-series	The series contains a unit root (non-stationary)	-4.512	0	Reject H_0	The PP test confirms that the series is stationary, supporting the ADF test results.
4	Breusch–Godfrey LM Serial Correlation Test	Detect serial correlation in residuals	No serial correlation exists in the residuals	1.184	0.315	Fail to Reject H_0	No evidence of serial correlation is detected in the regression residuals.
5	Breusch–Pagan Heteroskedasticity Test	Test constant variance of residuals	Residual variance is constant (homoskedasticity)	2.417	0.128	Fail to Reject H_0	The residuals exhibit constant variance, indicating homoskedasticity.
6	White Heteroskedasticity Test	Confirm absence of heteroskedasticity	Residual variance is constant (homoskedasticity)	3.162	0.204	Fail to Reject H_0	No evidence of heteroskedasticity is observed in the regression model.
7	Jarque–Bera Normality Test	Examine normality of residuals	Residuals are normally distributed	1.846	0.397	Fail to Reject H_0	Residuals are approximately normally distributed, satisfying the normality assumption.
8	Durbin–Watson Statistic	Detect first-order autocorrelation	No first-order autocorrelation exists	2.08	—	Accept H_0	The Durbin–Watson statistic is close to 2, indicating no first-order autocorrelation.
9	Ramsey RESET Specification Test	Evaluate functional form of the model	The regression model is correctly specified	0.864	0.461	Fail to Reject H_0	No evidence of model misspecification is detected, indicating that the functional form is appropriate.

Source: Author's estimation based on annual secondary data from MNRE, CEA, Ministry of Power, RBI Handbook of Statistics, India Energy Dashboard, and other official Government of India publications.

Note: Standard time-series diagnostic tests, including residual analysis, unit root tests, serial correlation, heteroskedasticity, normality, autocorrelation, and model specification tests, were performed to assess the validity and reliability of the estimated regression model.

Table 4.6 presents the results of the time-series diagnostic tests used to evaluate the reliability and validity of the Kinked Exponential Growth Model. The residual plot indicates that the residuals are randomly distributed around zero without any systematic pattern, suggesting an appropriate model fit. Both the Augmented Dickey–Fuller (ADF) test (test statistic = −4.286, $p = 0.001$) and the Phillips–Perron (PP) test (test statistic = −4.512, $p < 0.001$) reject the null hypothesis of a unit root, confirming that the series is stationary. The Breusch–Godfrey LM test ($p = 0.315$), Breusch–Pagan test ($p = 0.128$), White test ($p = 0.204$), Jarque–Bera test ($p = 0.397$), Durbin–Watson statistic (2.08), and Ramsey RESET test ($p = 0.461$) collectively indicate the absence of serial correlation, heteroskedasticity, non-normality, autocorrelation, and model misspecification, confirming the robustness of the estimated model.

Table 4.7. Hypothesis testing results on the structural change of renewable energy generation in India using the Kinked Exponential Growth Model

Hypothesis	*Test Statistic*	*Estimated Value*	*p-value*	*Decision*	*Interpretation*
H_0: The estimated growth rates before and after the pre-specified 2010 policy breakpoint are not significantly different.	t-test for Kink Coefficient (β_2)	4.83	0.000	Rejected	The positive and statistically significant kink coefficient indicates a statistically significant difference in the estimated growth rates before and after the pre-specified 2010 policy breakpoint.
H_0: The growth rate before and after the pre-specified 2010 policy breakpoint is the same ($\beta_2 = 0$).	Wald Test	23.33	0.000	Rejected	The post-break growth rate differs significantly from the pre-break growth rate.
H_0: The Kinked Exponential Growth Model is not statistically significant.	F-test	684.52	0.000	Rejected	The regression model is highly significant in explaining renewable energy growth.
H_0: The explanatory variables do not explain the variation in renewable energy generation.	Coefficient of Determination (R^2)	0.982	0.000	Rejected	Approximately 98.2% of the variation in renewable energy generation is explained by the model.
H_0: Residuals exhibit first-order autocorrelation.	Durbin–Watson Statistic	2.08	—	Accepted	The Durbin–Watson statistic is close to 2, indicating no evidence of first-order autocorrelation.

Source: Computed by the author based on the estimated Kinked Exponential Growth Model.

Note: Hypothesis testing was performed at the 1% significance level to examine structural change in renewable energy generation.

Table 4.7 provides the output of hypothesis testing results for the Kinked Exponential Growth Model. The null hypothesis of the absence of structural change is rejected at the 1% level of significance since the kink coefficient ($\beta_2 = 4.83$; $p < 0.001$) is statistically significant. Further, the Wald test result shows the presence of a significant difference in the growth rate before break and after break. The extremely significant value of the F-statistics (684.52) and coefficient of determination ($R^2 = 0.982$) show that the model is capable of explaining most of the variation in the data.

5. Discussion

The results show a large-scale structural change in renewable energy generation in India for 1991–2025. From descriptive statistics, there is evidence of considerable growth in generation capacity and investments, where solar energy presents the largest variance, showing the fast technology adaptation. In growth analysis, the yearly growth rate changed from 5.84% before the Electricity Act to 17.86% in the Green Energy Transition period. The Kinked Exponential Growth Model, estimated using a pre-specified policy breakpoint at 2010 corresponding to the launch of the Jawaharlal Nehru National Solar Mission (JNNSM), indicates that the estimated annual growth rate increased from 7.47% during the pre-policy period to 13.62% during the post-policy period. The observed acceleration coincides with major renewable energy policy initiatives implemented in India and should not be interpreted as establishing causality The high explanatory power of the model ($R^2 = 0.982$) indicates that the Kinked Exponential Growth Model provides an excellent fit to the observed data and effectively captures the long-term growth pattern of renewable energy generation. The observed acceleration in renewable energy growth coincides with major policy developments but should not be interpreted as evidence of a causal relationship.

6. Major Findings

1. Renewable energy generation in India increased substantially during the study period, rising from 12,547 GWh in 1991 to 258,764 GWh in 2025, with an average annual generation of 98,456 GWh, indicating remarkable long-term expansion of the renewable energy sector.
2. Renewable energy growth accelerated across successive policy regimes, with the Annual Growth Rate (AGR) increasing from 5.84% during the Pre-Electricity Act period to 17.86% during the Green Energy Transition period, reflecting progressively stronger growth performance.
3. The Kinked Exponential Growth Model revealed a statistically significant structural change in India's renewable energy growth trajectory. The estimated annual growth rate increased from 7.47% during the pre-policy period (1991–2009) to 13.62% during the post-policy period (2010–2025), representing an acceleration of 6.15 percentage points after the pre-specified 2010 policy breakpoint associated with the Jawaharlal Nehru National Solar Mission (JNNSM).
4. The estimated Kinked Exponential Growth Model exhibited excellent statistical performance, with a coefficient of determination (R^2) of 0.982, Adjusted R^2 of 0.979, an F-statistic of 684.52, and a Durbin–Watson statistic of 2.08, indicating high explanatory power, overall model significance, and the absence of first-order autocorrelation.
5. Descriptive statistical analysis indicated substantial expansion in renewable energy generation, installed renewable energy capacity, investment, and renewable energy share. Solar power generation exhibited the highest variability among all renewable energy sources, reflecting its rapid expansion during the study period.
6. The diagnostic tests confirmed the robustness and reliability of the estimated model. The ADF and Phillips–Perron tests verified stationarity, while the Breusch–Godfrey, Breusch–Pagan, White,

Jarque–Bera, Durbin–Watson, and Ramsey RESET tests indicated no serial correlation, heteroskedasticity, non-normality, or model misspecification.

7. Hypothesis testing rejected the null hypothesis of no structural change, confirming a statistically significant difference between the pre-2010 and post-2010 growth trajectories of renewable energy generation. These findings provide strong empirical evidence of India's accelerated renewable energy transition following the pre-specified policy breakpoint, while indicating temporal association rather than causality.

7. Policy Suggestions

1. The Government of India should strengthen and ensure the consistent implementation of long-term renewable energy policies to sustain the accelerated growth trajectory of renewable energy generation and support the country's clean energy transition.

2. Public and private investments should be expanded in renewable energy infrastructure, including transmission networks, smart grids, and energy storage systems, to improve the efficiency, reliability, and integration of renewable electricity generation.

3. Greater financial incentives, low-interest financing, tax benefits, and technological support should be provided for solar, wind, biomass, and small hydropower projects to accelerate renewable energy deployment across the country.

4. A comprehensive monitoring and evaluation framework should be established to periodically assess renewable energy policies, identify structural changes in growth patterns, and facilitate evidence-based policy formulation for future energy planning.

5. Priority should be given to promoting technological innovation, research and development, and modernization of renewable energy systems to improve generation efficiency, reduce production costs, and enhance the competitiveness of renewable energy technologies. This recommendation is consistent with the study's emphasis on technological advancement accompanying higher growth.

6. Integrated renewable energy planning should be aligned with India's long-term sustainable development, energy security, and net-zero emission objectives by encouraging coordinated action among central and state governments, regulatory institutions, and private stakeholders. This aligns with the study's focus on renewable energy planning and policy evaluation.

7. Future renewable energy policies should adopt a data-driven approach by incorporating periodic growth trend analysis and structural change assessment using advanced econometric techniques, such as the Kinked Exponential Growth Model, to support timely policy revisions and improve strategic decision-making in the renewable energy sector. This recommendation follows from the study's methodological contribution.

8. Conclusion

The research examined the growth trends and structural change in renewable energy generation in India during the period 1991–2025 using the Kinked Exponential Growth Model. The findings reveal substantial long-term growth in renewable energy generation, installed capacity, and investment, reflecting India's continued progress towards a sustainable energy transition. The growth analysis indicates that renewable energy generation expanded progressively across successive policy regimes, particularly following the National Solar Mission and other clean energy initiatives. The

Kinked Exponential Growth Model, estimated using a pre-specified policy breakpoint at 2010 corresponding to the launch of the Jawaharlal Nehru National Solar Mission (JNNSM), indicates that the estimated annual growth rate increased from 7.47% during the pre-policy period to 13.62% during the post-policy period. The model exhibited excellent statistical performance, with a high explanatory power ($R^2 = 0.982$), a statistically significant F-statistic, and no evidence of first-order autocorrelation. The observed acceleration in renewable energy growth coincides with major renewable energy policy initiatives, technological advancements, and increased investments in the sector; however, these findings should not be interpreted as establishing causal relationships. Overall, the study provides robust empirical evidence on the long-term growth pattern of renewable energy generation in India and offers valuable insights for future renewable energy planning and policy evaluation.

9. Limitations of the Study

There are some restrictions on the current research. First, the research is based solely on secondary time-series data, whose precision is determined by the reliability of official data sources. Secondly, the research is conducted for the period of 1991-2025, and, therefore, will not reflect possible future changes in trends of renewable energy. Thirdly, the Kinked Exponential Growth Model shows one breakpoint in total renewable energy trend, but does not consider possible occurrence of multiple breakpoints due to changing conditions in policy and markets. Finally, the research is concentrated on growth trends and structural change without taking into account causality of economic, technological and environmental factors that affect generation of renewable energy in India.

10. Scope for Further Research

Research can further expand this paper by using several structural break models like the Bai-Perron model or the Markov Switching Models in order to analyze more complicated trends in the growth pattern of renewable energy. Comparisons can be made through Indian states or between other developing nations in order to gain more general insight regarding the regional transition of energy. Additional research can focus on how policy actions, technology, foreign direct investments, carbon dioxide emissions, and economic growth affect the development of renewable energy.

Author Contributions

The study was conceptualized by Mr. Sanjiv Sarkar, designed the research methodology, collected and analyzed the secondary data, interpreted the findings and drafted the manuscript. The research was supervised by Dr. C. Venkatesh who contributed to the conceptualization and research methodology, reviewed and edited the manuscript, validated the findings and provided the academic supervision to the work. Both the authors contributed to the interpretation of the findings, have seen and approved the final manuscript and are responsible for all aspects of the work.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this research.

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