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India's Journey to Net Zero: A Case Study on Transitional Opportunities for Renewables Under C_{50} and C_{100} Scenarios

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Abstract: Global energy demand is increasing annually due to rising economic activities and population growth, making energy production a major greenhouse gas source. Current trends had alarmingly exceeded the 1.5ºC target as emissions surpass 53.8 Gt CO_2 eq. India, as a signatory to the United Nations Framework Convention on Climate Change (UNFCCC), aims for net zero by 2070 and 500 gigawatts (GW) of renewables by 2030, requiring urgent action to phase out fossil fuels and transition to clean energy. The present study aims to analyze the relative pathways to phase out fossil fuel-based electricity generation and assess the collective investment required for renewable electricity generation. Renewable electricity generation is growing steadily and currently constitutes about 43% of the total electricity being produced in the country (426.72 GW, excluding nuclear power). This study examines phased energy transition pathways through a case study, focusing on the C_{50} and C_{100} scenarios, which correspond to a 50% and 100% reduction in fossil fuel-based electricity generation, respectively. Using simulation-based modeling, the present study identified that in the C_{50} scenario, the total renewable electricity will have a 66% surge in 5 years. An advanced simulation of C_{100}'s complete phaseout of fossil fuel-based electricity generation can be attained with a surge of ~133% in renewable electricity generation. Both simulations widen the capital investment opportunities, ranging from 99.13 to 198.26 thousand crore INR annually with a proposed contributing share from the central, state, and private sectors reaching 47.38, 49.17, and 101.71 thousand crore INR, respectively, in the C_{100} scenario. Besides the government, huge private sector investment in the transition to renewables would be essential. Additionally, comprehensive policy reforms and increased public awareness of the role of renewable energy in climate change mitigation are important. The study urges a multi-stakeholder approach, including financial, technological, and policy reforms, for successfully achieving the energy transition targets of the country.

Keywords: energy transition, renewable energy, electricity generation, phase-out fossils, carbon neutral

1. Introduction

Energy is a basic need of the ever-growing global population that powers the industries, houses, and transport systems across the globe. The use of fossil fuels like oil, coal, natural gas, and diesel has contributed to almost one-third of the global greenhouse gas (GHG) emissions [1]. The beginning of industrialization has initiated the country's ambitions of getting developed industrially, economically, and technologically. This in turn led to an unsustainable utilization of the natural resources of the planet Earth. Unsustainable industrial development has led to the depletion of many natural resources, deforestation, reduction in biodiversity, and extinction of different species, and importantly, the modern-day challenges of global warming and climate change have emerged [2]. This has impacted the quality of the natural environmental components and has set in motion severe weather events like droughts, tsunamis, hurricanes, sea level rise, dynamics of rainfall patterns and duration, and many other catastrophes [3]. In a coal-dominated emerging economy like India, the combustion of fossil fuels is one of the major contributors to CO_2 emissions. India, as one of the fastest-growing economies, is surrounded by dual challenges: economic growth and balancing environmental sustainability. In the last few decades, the country has progressed significantly in agriculture, literacy, and industrial output. For example, the instance of the Green Revolution has helped India to transform its agricultural landscapes but also contributed to the depletion of groundwater and an increase in GHG emissions [2]. Moreover, the per capita CO_2 emission of the country has increased from 36 kg in the 1970s to 1590 kg in the year 2014, which is still less than most of the developed nations [2]. However, the pace of per capita CO_2 emissions is growing at an alarming rate. This increase will further accelerate the retrogressive dynamics of climate change led by air pollution. The retrogressive changing climate, along with resource depletion and environmental degradation, will increase human health risks like respiratory illness and cardiovascular diseases.

India is the second-largest energy consumer [4] and additionally the third-largest energy producer [5] after China. Nearly 50% of this energy is produced from coal alone. Electricity produced through conventional nonrenewable resources has surged the CO_2

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emissions in the country by 8.2% in the year 2023. This trend, coupled with global emission expectations of 53.8 Gt CO_2 eq, has recently breached the global target of keeping warming below 1.5ºC [6]. The composition of emitted effluents from thermal power plants has up to 187 different fatal chemicals released at a rate of 386 thousand tons annually to the environment. Most of them are classified as hazardous groups of pollutants. These pollutants are dynamic and accumulate in the environment and can potentially enter the food chain [4, 7]. These pollutants have different direct and indirect impacts on human health, leading to severe environmental pollution and deteriorating the quality of air, water, and soil [8]. The direct and indirect impacts have led to 16.79 lakh fatalities in 2019 alone [9] and 3.30 lakhs due to particulate matter exposure in 2020. There has also been an increase of about 55% in heat deaths between 2000–04 and 2017–21 in the country [10].

Anthropogenic emissions of GHGs are the major contributor to climate change. The energy sector has a major role in the emissions rising to ~82% [11]. This is because around 80% of the energy requirements globally are met by fossil fuels. The present estimates show that the emission reduction rates are much lower-paced, and the buffer period for developing new strategies that could fundamentally reduce global GHG emissions from energy sectors is decreasing [11]. In addition, by the year 2050, it is projected that GHG emissions will be >2.5 times higher for CO_2 and >2.8 times higher for fluorinated gases. The total GHG emissions will be more than twice the present emissions in the country [12]. India is ranked 4^{th} in terms of annual GHG emissions globally, and the estimated emissions from all of its sources accounted to be 244 crore tons of CO_2 eq. Energy production is one of the major contributors, releasing 92% of CO_2 through its production sectors, accelerating GHG emissions [13]. In addition to its own production, India is importing nearly 200 million tons of coal annually [1]. Though the direct support policies of the country are in line with the 2018 Allianz Climate and Energy Monitor, it is still ranked lower for the conditions of general investment opportunities as per the Allianz [1]. There is an immediate need to boost alternative sources of energy in order to reduce the direct and indirect impacts of fossil fuel burning for better human health and the environment of the country. In the advent of the climate crisis, to reduce the country's carbon footprint, India has taken several proactive measures. As a signatory to different international agreements, the country is aiming for the GHG emission intensity of gross domestic product (GDP) to be reduced by 20–25% from 2005 levels. India has made progress in the GHG emission reduction targets, yet several challenges surround transitioning to renewables from fossil fuels [1, 2].

India at COP26 (26^{th} Conference of Parties of UNFCCC) had announced its target of achieving net-zero emissions by 2070. In addition, India has also set its target of a 50% reduction in emissions by achieving 500 gigawatts (GW) of renewable energy capacity by 2030 with a reduction in GHG emission intensity of GDP by up to 35% by 2030 from 2005 levels [14, 15]. The net-zero goal is also supported by a study where a coal-based power generation peak is simulated by 2040, followed by a 99% reduction from 2040 to 2060 with a three-fold increase in solar power generation [14]. Progressing toward its ambitious goal, India has made remarkable progress and now, respectively, holds the 5th and 4th largest solar and wind power capacity across the globe. In addition to its ambitious goal of producing 500 GW of electricity from renewable sources, India has announced it will cut its cumulative emissions by one billion tons by the year 2030 [16]. In recent years, major works have been conducted on opportunities to explore available renewable sources of energy [1, 14, 17–19]. However, the investment opportunities in different renewable sectors with different target scenarios in specified time frames have not been explored rigorously yet. This has led to a knowledge gap in the transformation of an accelerated renewable energy sector in the country. The present article therefore aims to understand the investment opportunities in the renewable sector in India with the objective to analyze the annual investment opportunities in different renewable sectors of electricity generation in the country.

2. Methodology

The present study is primarily based on secondary data sources, and a comprehensive survey of literature has been carried out. We conducted a systematic review to identify key trends, challenges, and opportunities in transitioning to renewable energy in the context of India. While the current study focuses on scenario development, we recognize that integrating empirical data – such as historical energy transition trends or case studies from other regions – would strengthen the scientific basis of the findings.

The search has also been extended to published articles to online news/article feeds for parameters including capital costs of hydropower, wind power, solar power, biomass power, waste-to-electricity, and small hydropower (Table 1A). The total installation and operational cost and total energy potential of the plant were used to calculate per GW capital cost for each of the renewable power sectors. The obtained capital cost for each renewable power plant was divided by the total installed potential of the specific project to calculate the capital cost for each GW of installed potential.

The reduction target for fossil fuel-based electricity generation at C_{50} (cutting fossil fuel-based electricity generation by 50%) and C_{100} (cutting fossil fuel-based electricity generation by 100%) in the next 5 years is set. The cumulative reduction of fossil fuel-based electricity generation at C_{50} and C_{100} was calculated using the following Equation (1):

$$CR–C_{50} = \Sigma(CPi \times 0.5) \text{ and } CR–C_{100} = \Sigma(CPi \times 1.0) \quad (1)$$

where "CR" is the cumulative reduction (in the C_{50} and C_{100} scenarios), "CP" is the current installed potential, and "i" represents the fossil fuel-based power generation sectors (coal, lignite, gas, or diesel).

The cumulative reductions in the C_{50} and C_{100} scenarios were distributed among the fossil fuel-based power sectors as per their present percent share of the total power generation. Therefore, the total reduced electricity generation from fossil fuel-based sectors at C_{50} and C_{100} has been distributed into the renewable energy sectors as per their present percent share of installed capacity [20], excluding the present demand for surplus electricity and the nuclear power sector. This was calculated using the following developed Equation (2):

$$\begin{aligned} CPI–C_{50} &= \Sigma[P^{i}_{Curr} + (Pi \times CR–C_{50})] \text{ and} \\ CPI–C_{100} &= \Sigma[P^{i}_{Curr} + (Pi \times CR–C_{100})] \end{aligned} \quad (2)$$

where "CPI" is the cumulative potential increment (in the C_{50} and C_{100} scenarios), "P^{i}_{Curr}" is the current installed potential of the "i^{th}" renewable power sector, "Pi" is the present proportion of the i^{th} renewable power sector to the total renewable installed capacity, and "CR" is the cumulative reduction (in the C_{50} and C_{100} scenarios).

The per GW capital costs obtained by the division method have been multiplied by the progressive installed capacity of different renewable electricity generation sources [20] and are extrapolated for future simulations. The annual investment capital cost for each renewable power sector and the cumulative annual investments for each of the scenarios were calculated using the following Equation (3):

$$\begin{aligned} ACI-C_{50} &= \Sigma({}^{i}PI-C_{50} \times GW^{i}_{Cost}) \text{ and} \\ ACI-C_{100} &= \Sigma({}^{i}PI-C_{100} \times GW^{i}_{Cost}) \end{aligned} \tag{3}$$

where "ACI" is the annual capital investment (in the C_{50} and C_{100} scenarios), "${}^{i}PI$" is the installed potential increment of the "i^{th}" renewable power sector (in the C_{50} and C_{100} scenarios), and "GW^{i}_{Cost}" is the per GW capital cost for the "i^{th}" renewable power sector.

3. Results

In the current scenario, the total peak demand for electricity has been observed to have a growth of 104% from 2009–10 to 2023–24 (243.27 GW) in the country. This significant increase shows the rapid developments in urbanizing, industrializing, and changes in lifestyle across the country. The supply and demand deficit of electricity has also declined on a polynomial scale, and the current deficit of peak demand is 3.34 GW, as Figure 1 [20] shows. Among the total electricity being produced in the country from all sources, nearly 57% is contributed by fossil fuel-based power sectors, like coal (49%), natural gas (6%), lignite (1.6%), and diesel (0.14%).

The total electricity produced from different nonrenewable (fossil) and renewable sources is >426 GW in the country, excluding nuclear. In the year 2023–24, electricity produced from nonrenewable sources, like coal, lignite, gas, and diesel, remained 1.33 times higher than the total electricity produced from renewable sources (183.50 GW) (excluding nuclear), as Figure 2 [20] shows. Thermal power plants where coal is the sole raw material are still dominating the total electricity production in the country, with >210 GW of electricity being produced every year and diesel being the least with about 0.6 GW of production, as Figure 3 [20] shows. Following coal, the contribution of gas stands second with 25.04 GW to the total power generation surplus from fossil fuel-based sources.

To reduce the present surplus of electricity production (excluding the present surplus demand) in the C_{50} and C_{100} scenarios in the next 5 years, it is necessary to accelerate energy production from all renewable sources. This transition is essential in meeting the sustainable development goals and addressing the environmental issues that exponentially erupted while depending on the conventional fossil fuel-based power generation in the country. Specifically, renewable energy production will need to be increased by approximately 1.7 times for the C_{50} scenario and 2.3 times for the C_{100} scenario. Achieving this scale will help to achieve energy production from renewables to reach around 305 GW and 426 GW in the C_{50} and C_{100} scenarios, respectively.

The simulated reduction targets for fossil fuel-based installed capacity in the country indicate a cumulative phaseout of 121.61 GW under the C_{50} scenario and 243.22 GW under the C_{100} scenario (Table 1). As the dominant fossil fuel in India's power sector, coal power plants account for the largest share of this reduction, with a projected decline of 105.48 GW under C_{50} and 210.97 GW under C_{100}. The natural gas-based power sector is expected to decrease its installed capacity by 12.52 GW under C_{50} and 25.04 GW under C_{100}. Meanwhile, lignite and diesel, the smallest contributors to India's fossil fuel-based power sector, are projected to see reductions of 3.31 GW and 0.29 GW, respectively, in the C_{50} scenario.

Figure 1
Peak electricity demand and availability in the country (GW – gigawatt)

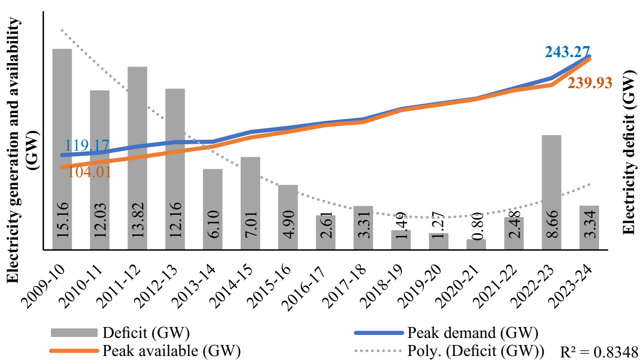


Figure 2
Present surplus of energy generation and projection from all the sources excluding nuclear (GW – gigawatt)

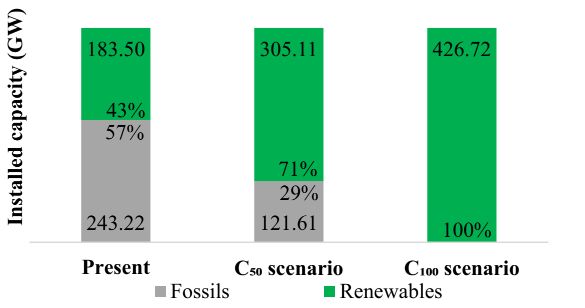


Figure 3
Present surplus of electricity generation from different fossil fuels (GW – gigawatt)

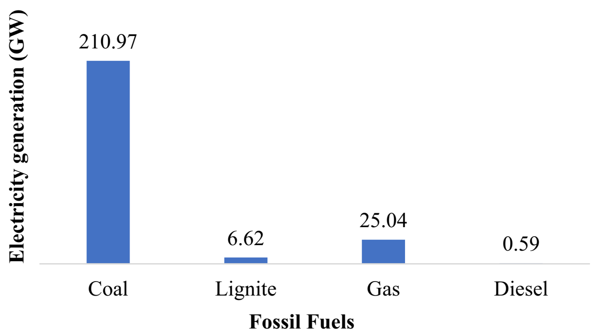


Table 1
Installed potential (GW) reduction targets from different fossil-based power sectors under simulated scenarios

Power sectors	C_{50} scenario	C_{100} scenario
Coal	105.48	210.97
Lignite	3.31	6.62
Gas	12.52	25.04
Diesel	0.29	0.59
Total	121.61	243.22

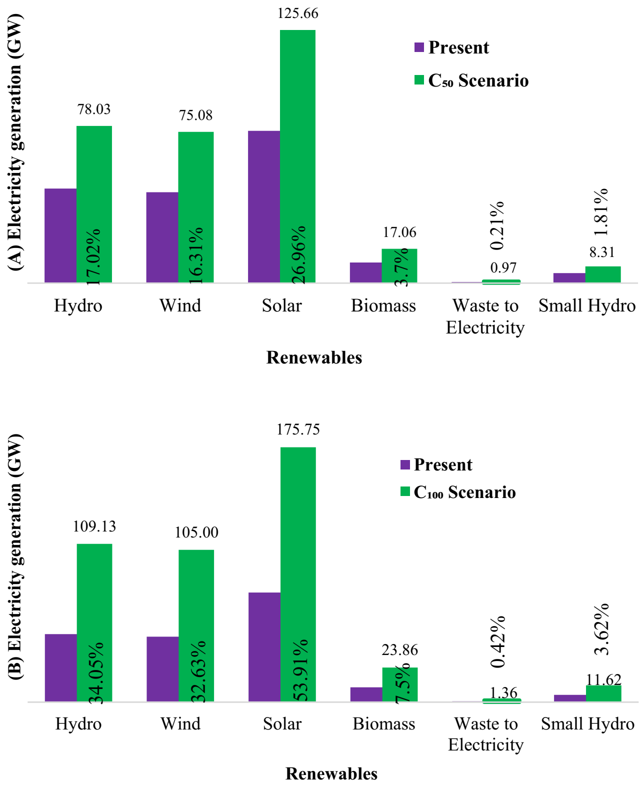
The present total installed capacity of all the renewable energy sources in India has been observed at 183.50 GW (excluding nuclear), highlighting the country's significant progress in harnessing renewable energy. Among different sectors that contribute to renewable energy generation, solar energy stands out as the largest contributor with an installed capacity of 75.58 GW. Following solar, hydropower accounts for 46.93 GW, wind energy contributes 45.15 GW, biomass energy contributes 10.26 GW, small hydro shares a contribution of 5 GW, and waste to electricity contributes 0.58 GW. India's energy potential from renewable sources is solar (749 GW), wind (695 GW), hydro (145 GW), small hydro (20 GW), biomass (18 GW), and waste-to-electricity (3.7 GW) (Table 3).

Table 2
Shared electricity installed potential increments (GW) of renewables under simulated scenarios

Power sectors	C_{50} scenario	C_{100} scenario
Hydro	31.10	62.20
Wind	29.92	59.85
Solar	50.09	100.17
Biomass	6.80	13.60
Waste-to-electricity	0.39	0.77
Small hydro	3.31	6.62
Total	121.61	243.22

Thus, the total progressive shift of electricity produced from all renewable resources (excluding nuclear) has to be increased to 66.27% at C_{50} and 132.55% at C_{100} (Table 2). As per the available literature, the present share of electricity production from different renewable sources has also been estimated. Electricity generated from solar has to be increased by 27.29% and 54.59% in the C_{50} and C_{100} scenarios, respectively (Figure 4), to achieve a progressive installed potential of 125.66 GW in the C_{50} scenario and 175.75 GW in the C_{100} scenario. This is 16.8–23.5% of the total solar energy potential of the country in both scenarios. Similarly, 16% and 33% increments have been projected for wind power generation, respectively, for both scenarios raising its present potential to 10.8–15% at C_{50}–C_{100}, respectively, from 6.5% of the total. This will help to achieve a total installed potential of 75.08 GW in the C_{50} scenario and 105 GW in the C_{100} scenario. The biomass power generation has a projection simulation of 4% and 7% to generate 17 and 24 GW of electricity in the C_{50} and C_{100} scenarios, respectively, in the next 5 years. With a 2.73% share, small hydropower generation has also been projected to increase its potential to around 8 GW in the C_{50} scenario and 12 GW in the advanced simulation of C_{100} in the stipulated time. Electricity produced from the waste-to-power plants has a major opportunity to increase from the present potential of 0.58 GW to 0.97 GW in the C_{50} scenario and to 1.36 GW in the C_{100} scenario (Table 3). The renewable energy sector is expected to experience substantial growth under the simulated transition scenarios (Table 2). To compensate for the projected reduction in fossil-based generation, an additional 121.61 GW and 243.22 GW of renewable capacity will be required under the C_{50} and C_{100} scenarios, respectively (Table 2). Solar energy, which already holds the largest share of installed renewable capacity in India, is projected to see the highest increase, with additions of 50.09 GW under C_{50} and 100.17 GW under C_{100}. Wind power, the second-largest renewable energy source, is expected to expand by 29.92 GW under C_{50} and 59.85 GW under C_{100}. Meanwhile, hydropower, including both large and small hydro projects, is simulated to grow by 34.41 GW under C_{50} and 68.82 GW under C_{100}.

Figure 4
The proportion of increments required in different sectors of renewables in the next 5 years (except nuclear): (A) present to the C_{50} scenario and (B) present to the C_{100} scenario (GW – gigawatt)



However, the C_{50} and C_{100} scenarios will require huge capital investments and opportunities for desired outcomes of the energy transition pathways. Solar photovoltaics, which is the major player in green electricity at present, has an annual capital investment opportunity of 32.05 thousand crore INR to uplift its installed potential of 125.66 GW in the C_{50} scenario. The present simulated requirements are further increased with the advanced simulation of the C_{100} scenario, where annual capital investments of 64.11 thousand crore INR would enable the increase in its installed potential to 175.75 GW (Figure 5; Table 3). As with the present dynamics toward energy being produced from biomass, the same industry has to come up with its relative share of capital investment opportunities. Currently, the biomass-to-energy power industry has the potential to attract annual capital investments of 8.16 thousand crore INR at C_{50} and 16.32 thousand crore INR at C_{100} annually (Figure 5) for the next 5 years. The cumulative annual investment opportunity for the next 5 years will rise to 99.13 thousand crore INR at C_{50} and 198.26 thousand crore INR at C_{100} in the country (Table 3).

4. Discussion

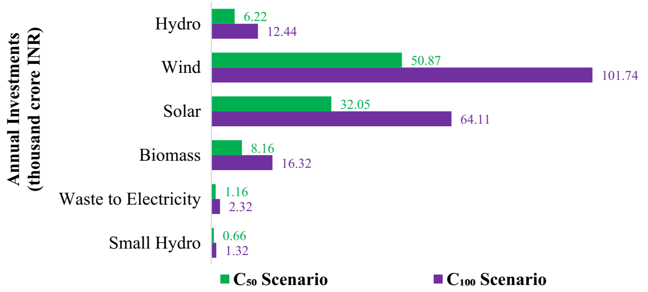
India's commitment to COP26 drew significant attention to various pathways through which emission reduction targets of the country can be set and initiated. Among the major sectors contributing

Table 3
Details of the electricity production requirements from renewable sources in the next 5 years at C_{50} and C_{100} scenarios

Renewables	Present Production (GW) [20]	Total Potential (GW)*	C_{50} scenario		C_{100} scenario		Annual capital investments (thousand crore INR)	
			Production (GW)	Proportion (%)	Production (GW)	Proportion (%)	C_{50} scenario	C_{100} scenario
Hydro	46.93	145	78.03	16.95	109.13	33.90	6.22	12.44
Wind	45.15	695	75.08	16.31	105.00	32.62	50.87	101.74
Solar	75.58	749	125.66	27.29	175.75	54.59	32.05	64.11
Biomass	10.26	18	17.06	3.71	23.86	7.41	8.16	16.32
Waste-to-electricity	0.58	3.7	0.97	0.21	1.36	0.42	1.16	2.32
Small hydro	5.00	20	8.31	1.80	11.62	3.61	0.66	1.32
Total	183.50	1038.65	305.11	66.27	426.72	132.54	99.13	198.26

Note: INR = Indian National Rupee; GW = gigawatt; *Table 2A

Figure 5
Annual progressive capital at C_{50} and C_{100} scenarios in the next 5 years (INR – Indian National Rupee)



to GHG emissions in the country, the power generation sector is one of the major emitters of GHGs, responsible for almost 75% of the total emissions [14]. Being a developing country, India is surrounded by major challenges for basic developmental needs, and ensuring a stable and surplus supply of energy is one of the most crucial requirements. With the country's growing demand for electricity, in addition to the exponential growth of the population, seeking pathways for emission reduction so as to reverse the breach of the 1.5ºC target is essential [6]. India is the most populous country, and the per capita electricity consumption of 1297 kilowatt-hours is among the lowest of the global average [21]. However, more than half of this electricity demand is fulfilled by using fossil fuels, such as coal, the stock of which is limited but is also a large contributor to the CO_2 emissions due to burning in power plants. The present dependence of the country on such fossil-based power sources would pose a dual challenge for India. These are balancing between economic needs and infrastructural development while addressing the critical environmental issues of GHG emissions. To reduce the impact of emissions, India needs to be ready for the formulation and implementation of emission reduction strategies and targets in different simulations for the future, which will be for diverse socioeconomic and technological scenarios. Robust situation simulation and predictive models could support these targets in identifying the feasible pathways to energy transition to renewable sources.

The C_{50} simulation presents an immediate opportunity to accelerate renewable electricity generation, reducing dependence on fossil fuels. This scenario could drive a 66% growth in India's renewable-based electricity production, enabling the country to achieve its G20 commitment of 63% renewable energy well before the 2050 target [22]. The C_{50} transition is 1.7–4.3 times faster than previous assessments [23, 24], which projected a gradual shift until 2070, lacking a robust near-term transition strategy. Additionally, the C_{50} investment is 1.14 times higher than prior cost analyses focused only on pollution control, highlighting its economic feasibility.

Achieving C_{50} requires strong renewable energy policies, grid stability improvements, storage expansion, and incentives for adoption. It could also lead to a 10% annual reduction in fossil fuel-based electricity, significantly contributing to national and global CO_2 reduction targets. Key drivers include the increasing affordability and scalability of solar photovoltaics and wind energy, aligning with global recommendations for a six-fold renewable energy expansion to limit warming below 1.5°C [25, 26]. The C_{50} scenario supports this trajectory, projecting a 3–6-fold (52.4–84.9%) increase in renewable production. An even more ambitious C_{100} simulation envisions a full fossil fuel phaseout within 5 years, making India a global leader in energy transition. This would require scaling renewable capacity 6–8 times the current levels, aligning with net-zero targets [27]. Both C_{50} and C_{100} scenarios affirm India's potential for rapid energy transition, in line with global commitments to generate 270 GW of renewable energy [18]. Besides reducing GHG emissions, these scenarios address environmental pollution and energy security challenges [22, 27]. A complete fossil fuel phaseout demands targeted investments in solar, wind, and energy storage to ensure grid reliability while retiring coal plants. The C_{100} scenario also emphasizes economic growth, fostering green infrastructure, job creation, and industrial expansion. Reports suggest that enhancing energy efficiency and investing in renewable sectors can boost GDP and employment while reducing fossil fuel reliance [22, 26].

India has explored only 17.7% of its total renewable installed potential, and with its ambitious goal, it can attain a 28% surplus of renewable energy under the C_{50} scenario. This scenario can also help in attaining the individual contribution toward a global renewable energy supply of 70–80% of total electricity by the year 2050 [28]. To achieve the ambition of becoming a phaseout and net-zero emitter country, the estimated annual capital investment ranges between 99.13 and 198.26 thousand crore INR, including the extension and setting up of new renewable energy stations. Excluding the growth of energy sectors and the surplus demand, accessing only 40% of its total renewable installed potential, India can be a renewable-based hub for electricity generation. Corresponding to the current shares, the investment contributions of the central sector, state sector, and private sectors are 23.69–47.38 thousand crore INR, 24.58–49.17 thousand crore INR, and 50.58–101.71 thousand crore INR [20], respectively, for C_{50}–C_{100} scenarios. The least cost target forwarded by Deshmukh et al. [17] is also 35% lower than our simulated scenario at C_{100}. This may be because of the non-consideration of all avenues of the renewable power sectors for simulating energy transition by 2030. These investment opportunities by the central, state, and private sectors can achieve a complete energy transition and also fulfill the target of net-zero emissions from the electricity sector. In addition to this, there is also a requirement to reform (pull and push) the energy and allied policies. This includes initiatives on offshore wind policy, an increase in the promotion of electric vehicles, opening and easing the terms of green electricity, and introducing a green day-ahead market for the trade of renewable energy [29]. India's peak electricity demand is projected to increase by 13.95% and 48.97% in 2026–27 and 2031–32, respectively, to 277.20 GW and 366.39 GW (Figure 1A) [30]. This expanding peak demand is 14.14% lower than our projected installed capacity of 426.72 GW under the C_{100} scenario for the year 2029–30. In addition to these reforms, the C_{50} scenario can sufficiently boost the reduction of the country's dependency on fossil fuel-based electricity generation and, most importantly, on coal.

The fossil fuel-based energy transition under C_{50} and C_{100} scenarios assessed in the study has significant societal implications. Progress toward alternative and clean sources of energy production will significantly reduce the amount of pollutants released into the environment from the conventional power sectors. This can help to uplift the air quality, particularly in the densely populated urban localities of India. Moreover, this transition could lead to a boost in employment in the sector associated with alternate energy sources, like in the manufacturing, installation, and maintenance of infrastructures. An enhanced job opportunity is indirectly related to improvements in livelihood standards regionally. The decentralized energy sectors, like small hydropower and rooftop solar, can enhance access to clean energy in the remote regions of the country. This will further improve livelihood quality and economic stability in such remote locations, a situation aligning well with the Sustainable Development Goals (SDGs), such as Affordable and Clean Energy (SDG 7) and Decent Work and Economic Growth (SDG 8). The simulated scenarios of energy transition could further strengthen the country's scalable models of energy transition for other developing nations aiming to attain the energy transition goals toward alternative, clean, and green sources of power generation.

5. Conclusion and Recommendations

This study outlines India's simulated pathways for achieving net-zero emissions through renewable energy expansion. The C_{50} and C_{100} scenarios present a transformative vision for the country's energy future. Under C_{50}, a renewable energy shift of 0.21–27.29% could increase its share in electricity generation from 43% to 71%. The C_{100} scenario envisions a completely carbon neutral of fossil fuels, leading to 100% renewable-based electricity generation. Achieving these targets requires an annual capital investment of 99.13–198.26 thousand crore INR, a feasible range for India's current economic landscape. Central, state, and private sector investments could range from 23.69–47.38, 24.58–49.17, and 50.85–101.71 thousand crore INR, respectively. This energy transition offers a viable trajectory for India's net-zero goals, with both domestic benefits and international influence – setting an example for other developing nations. However, realizing these scenarios requires policy reforms, public awareness, and streamlined regulations for green electricity production and use. A comprehensive approach integrating technological, economic, and policy strategies will be essential to establishing a sustainable renewable energy system in India.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are presented within the manuscript and in the Appendices.

Author Contribution Statement

Panna Chandra Nath: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Aditya Kumar Joshi:** Validation, Writing – review & editing, Supervision. **Arun Jyoti Nath:** Formal analysis, Writing – review & editing, Visualization, Supervision.

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Appendix I

Table 1A
Data sources for capital and installation cost of the renewable power sectors

Power sector	Article URL
Hydro power	https://www.financialexpress.com/business/industry-pumped-hydropower-storage-ge-to-set-up-1-5-gw-capacity-for-3-indian-units-2482890/
Wind power	https://energy.economictimes.indiatimes.com/news/renewable/replacing-low-capacity-old-windmills-with-higher-powered-machines-uneconomical-now/103823369
Solar power	https://www.firstgreen.co/how-much-does-it-cost-to-set-up-a-1-gw-integrated-solar-module-manufacturing-plant/#:~:text=However%2C%20setting%20up%20an%20integrated,silica%2C%20works%20out%20to%20INR32bn
Biomass power	https://www.scribd.com/document/631975695/What-is-the-Cost-of-Waste-to-Energy-Projects-in-India-Ankur-Scientific-pdf
Small hydro	https://www.financialexpress.com/business/industry-pumped-hydropower-storage-ge-to-set-up-1-5-gw-capacity-for-3-indian-units-2482890/

Table 2A
Data sources for total installed potentials of renewable power sectors in the country

Renewables	Total potential (GW)	Article/report URL
Hydro	145	https://powermin.gov.in/en/content/faqs-hydropower#:~:text=The%20hydropower%20potential%20of%20India,of%20around%2085%2C%20000%20 MW.
Wind	695	https://niwe.res.in/department_wra_est.php#:~:text=The%20estimated%20installable%20potential%20at,102788%20 MW%20(See%20the%20Table.
Solar	749	https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2023/08/2023080211.pdf
Biomass	18	https://www.ijert.org/research/biomass-energy-potential-in-india-a-review-IJERTCONV9IS11012.pdf#page=1.00&gsr=0
Waste to Electricity	3.7	https://doi.org/10.1016/j.eti.2023.103017
Small hydro	20	https://doi.org/10.1016/j.rser.2015.05.075

Figure 1A
Graphical abstract