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Original Research

Addressing Climate Change Through Renewable Energy Generation for Sustainable Development in India: Challenges, Current and Future Status

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Abstract: The rapid population and economic growth in India have led to a significant rise in energy demand. Meeting this demand through renewable energy is critical, as fossil fuel-based energy generation contributes heavily to greenhouse gas emissions. Renewable energy development offers a sustainable and comprehensive approach to addressing the dual challenges of climate change mitigation and energy security. This paper evaluates the current status of renewable energy development in India and its role in mitigating the adverse effects of climate change. A detailed analysis of trends in solar, wind, and hydropower development reveals that India's installed solar capacity is 82 GW, with an additional 88 GW under development. Wind energy accounts for approximately 46 GW of installed capacity, with 32 GW under development. Hydropower contributes 47 GW of installed capacity, with 18 GW under development. Together, these sources amount to approximately 175 GW of renewable energy capacity Despite significant progress, India faces substantial challenges in achieving its ambitious renewable energy target of 500 GW by 2030. This paper highlights various programs initiated by the Government of India to promote renewable energy and ensure sustainable development. Additionally, it identifies key challenges in meeting the targets and recommends innovative solutions to overcome these hurdles, paving the way for a sustainable energy future.

Key Words	Climate, Renewable energy, sustainable development goals, India
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1. Introduction

The United Nations Department of Economic and Social Affairs (UN DESA) has projected global population to range between 9.4 and 10.1 billion by 2100, depending on the fertility rate scenario (UN DESA, 2019). As this growth continues, the demand for essential resources such as food, water, and shelter will increase, creating significant environmental challenges. To ensure our continued existence, it is imperative that we adapt and embrace a lifestyle that fosters harmony with the natural world (Pandey, 2002). A major driver of economic growth is energy. The International Energy Agency (IEA, 2022) predicts a 1.2% annual increase in global primary energy demand from 12,300 million tons of oil equivalent (MTOE) in 2008 to 16,700 MTOE by 2035, marking a 40% increase overall (World Energy Outlook 2010). Environmental concerns are intricately intertwined with various factors such as population dynamics, technological advancements, economic paradigms, and socio-political considerations. Changes in driving forces including population growth, lifestyle choices, technological innovations, and socio-economic strategies have significantly impacted the global climate system. The Intergovernmental Panel on Climate Change (IPCC) has warned that human activities, particularly the burning of fossil fuels, have led to a significant rise in global temperatures (IPCC, 2021).

The driving forces described by Doos (1995) have notable impacts, particularly on greenhouse gas (GHG) emissions, affecting both the natural environment and the ecosystem crucial for human sustenance. The proliferation of industries has led to heightened utilization of energy resources, consequently escalating the emission of GHGs into the atmosphere, thereby playing a pivotal role in climate alteration. Various GHGs such as CO_2, CH_4, and N_2O are generated through natural and human-induced activities. While natural mechanisms exist for removing substantial quantities of GHGs from the atmosphere, anthropogenic activities have surpassed the Earth's natural capacity to mitigate these gases effectively. A major contributor of CO_2 emissions is the power generation sector, mainly due to the burgeoning demand for fossil fuel-powered plants in developing nations (Soares, 1999). Anthropogenic CO_2 emissions are principally attributable to suboptimal combustion of fossil fuels and biomass. Additionally, non-methane hydrocarbons are generated through anthropogenic activities of biomass and fossil fuel burning and solvent usage. These pollutants undergo atmospheric reactions with sunlight, contributing to the formation of tropospheric Ozone (O_3) - a significant GHG (Soares, 1999). To reduce the adverse effects of climate change, transitioning to green energy sources is crucial. By decreasing dependence on fossil fuels, this shift can manage climate change challenges and energy security concerns. Renewable energy presents a promising solution as it generates power without emitting GHG and relies on abundant, sustainable resources. This approach aligns with global efforts to promote sustainability and combat climate change, encouraging policymakers to prioritize renewable energy in their strategies. For a country like India, with abundant solar, wind, and biomass resources, transitioning to renewable energy is not only feasible but also economically advantageous.

India has demonstrated a strong commitment to combating climate change by aligning its energy and environmental policies with the agenda of the Paris Agreement. As a signatory, the country has pledged to achieve 40% of its installed power capacity from non-fossil fuel sources by 2030 and to reduce the emissions intensity of its GDP by 33-35% from 2005 levels. These targets underscore India's proactive role in addressing the global climate crisis while maintaining its developmental trajectory. Renewable energy development is central to fulfilling these commitments. By transitioning to renewable energy, India aims to reduce its reliance on fossil fuels, which are not only major contributors to GHG emissions but also a significant source of air pollution. Air pollution, primarily from the combustion of fossil fuels, poses severe health risks, including respiratory and cardiovascular diseases. The adoption of cleaner energy sources is expected to significantly improve air quality, particularly in urban areas where pollution levels are alarmingly high, thereby enhancing public health and reducing health care burdens.

The development of the renewable energy sector has significant impact on socio-economic status also. Therefore, the government of India (GOI) has identified renewable energy as a major driver for job creation. From manufacturing and installation to maintenance and research, the sector offers diverse employment opportunities, contributing to economic development. Given the multifaceted advantages of renewable energy, the major objective of the present research is to critically evaluate the status of renewable energy development in India with a focus on its contribution in combating climate change. The intent is to provide a comprehensive understanding of the role of renewable energy in India's climate action strategy, offering insights that can inform future policies and initiatives. This paper also reviews several programs designed to mitigate the adverse impacts of climate change in India, with a focus on achieving Sustainable Development Goals (SDGs). The challenges associated with achieving the renewable energy target of 500 GW by 2030, and innovative solutions to address these challenges are also discussed in the paper.

2. Methodology and Data Sources

The methodology of this research involves a comprehensive approach to addressing climate change in India through renewable energy development. The first step is to describe the causes and impacts of climate change, focusing on key drivers such as GHG emissions from industrial activities, deforestation, and fossil fuel consumption. The environmental and socio-economic impacts, including rising temperatures, extreme weather events, and threats to agriculture and water resources, are described to underscore the urgency of mitigation efforts. Next, the study discusses India's plan for climate change mitigation, highlighting national strategies like the National Action Plan on Climate Change (NAPCC) and commitments under the Paris Agreement. Key initiatives such as the National Solar Mission, National Water Mission, and the Green India Mission are reviewed to assess their contributions toward achieving climate goals. The role of Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), in combating climate change is discussed next. The alignment of these SDGs with India’s renewable energy and sustainability objectives is examined to emphasize their importance.

The next step in the methodology is to include an evaluation of the current status of renewable energy development in India, analyzing progress in solar, wind, and hydropower capacities and identifying regional and sectoral gaps. The study then identifies challenges in meeting renewable energy targets, such as infrastructure limitations, financial constraints, and policy inconsistencies. Finally, innovative solutions are recommended to overcome these challenges and ensure the achievement of India’s renewable energy target of 500 GW by 2030.

The data on installed capacity and capacity under development for wind, solar and hydro power has been sourced from the Central Electricity Authority (CEA, 2023) and the Ministry of Power, GOI, recognized as the most reliable sources for information on these forms of renewable energy. Other sources of data on installed capacity include the NITI Aayog – the apex policy making body of India. The data pertaining to the National Action Plan on Climate Change has been obtained from the Ministry of Environment and Forest, GOI.

3. Causes and Impacts of Climate Change in India

Climate change refers to long-term alterations in climate patterns, driven by natural processes, external factors, or human activities that modify atmospheric composition. The IPCC (IPCC 2022) emphasizes variability over extended periods, while the UNFCCC specifically attributes change to human actions. The environmental protection agency (EPA) highlights significant shifts in temperature, precipitation, and wind patterns over decades. The fifth assessment report of IPCC (IPCC, 2022) suggests that extreme hydrological events are more likely to intensify due to climate change. These changes are expected to impact natural ecosystems and socio-economic systems, as noted in India's National Communications Report to the UNFCCC (INC, 2004). The second working report by the United Nations anticipates significant coastal erosion due to the escalating sea levels, projected to rise by approximately 40 cm. This surge is attributed to the accelerated melting of glaciers in the Himalayas and Hindu-Kush ranges. The ramifications include the potential displacement of around half a million individuals in India, primarily due to heightened flooding in coastal regions.

Additionally, there are concerns about the escalation of salinity levels in both groundwater in the Sundarbans and surface water in coastal areas (Bindoff et al. 2007). Research indicates a decline in mountain glaciers and snow cover across both hemispheres. This widespread reduction is strongly linked to climate change, a contributing factor to the observed rise in sea levels. In the Indian mainland, it is estimated that a rise in sea levels would inundate approximately 5,763 square kilometres of coastal land, displacing an estimated 7 million residents.

The dominance of fossil fuel-based power generation, including coal, oil, and gas has led to significant adverse climatic changes in India. With significant population growth in recent decades, energy demand has grown substantially, leading to a sharp increase in carbon dioxide emissions (Asumadu-Sarkodie & Owusu, 2016a). Traditional fossil fuel-based energy production emits between 0.5–0.97 kg of carbon dioxide (CO_2) per kWh (Abdallah & El-Shennawy, 2020). As of March 2019, atmospheric CO_2 levels have risen to 414.8 ppm, far exceeding the recommended optimal level of 350 ppm. Global CO_2 emissions currently surpass 36.8 Gt, with India contributing approximately 6.7% (based on 2016 data) (O'Neill, 2020; Suresh & Rao, 2017). In 2007, India emitted 1221.76 Mt of CO_2, 20.56 Mt of CH_4, and 0.24 Mt of N_2O, totaling approximately 1727.71 Mt CO_2 equivalent. The largest share (37.8%) was contributed from electricity generation, followed by industry (21.7%), agriculture (17.6%), transportation (7.5%), and residential (7.2%) sectors (MoEF, 2010).

While a thorough compilation detailing the effects of climate change in Table 1 on India remains elusive, three key impacts stand out: (1) the rising sea levels resulting in the inundation of coastal regions, (2) the detriment to agriculture and infrastructure caused by more frequent extreme weather events, and (3) the various other environmental concerns. Each of these phenomena, among others, presents significant threats to India's well- being.

Table 1-Climate change impact parameters

S. No.	Causes	Details	Impacts

01.	Meteorological effects	Sea-level rise and extreme weather events; altered rainfall patterns in India, leading to more frequent droughts and floods	Such changes cause altered weather patterns, irregular rainfall, extended droughts, and higher evaporation rates, contributing to water scarcity as evidenced in many parts of India (Kampanad and Sharif, 2020).
02.	Greenhouse emissions	The combustion of fossil fuels for energy production, transportation, and industrial activities releases GHGs like CO2, CH4 and N2O in the atmosphere, traps heat and cause global warming (IPCC, 2021).	Rising global temperatures and sea levels (IPCC, 2021). Heightened frequency and severe weather events like heatwaves, droughts, and storms (IPCC, 2014b). Ocean acidification due to increased absorption of CO_2 (Doney et al., 2009)
03.	Himalayan Glacial Retreat	Glaciers in the Himalayas are retreating at an alarming rate due to rising temperatures, threatening water resources and increasing the risk of glacial lake outburst floods (Bajracharya et al., 2015).	Reduced water availability for agricultural, domestic, and industrial uses (Immerzeel et al., 2010) Increased risk of glacial lake outburst floods, threatening downstream communities (Bajracharya et al., 2015)
04.	Deforestation and Land-Use Changes	The destruction of forests and other natural habitats, along with changes in land use, reduces the ability of the earth to absorb and store carbon, contributing to increased atmospheric CO_2 levels (Houghton et al., 2012).	Loss of biodiversity and habitat fragmentation (Newbold et al., 2015). Disruption of ecosystems and their services (Foley et al., 2005). Increased soil erosion and desertification (Lal, 2004).
05.	Agricultural Activities	Livestock farming, rice cultivation, and fertilizer utilization release CH_4 and N_2O, which are intoxicating GHGs (Tubiello et al., 2015).	Contribution to GHG emissions, particularly methane and nitrous oxide (Tubiello et al., 2015). Soil degradation and water pollution from excessive fertilizer use (Tilman et al., 2002).
06.	Extreme Heat Events	India has experienced an increase in the frequency and intensity of heatwaves, with severe impacts on human health, agriculture, and ecosystems (Rohini et al., 2016).	Heat-related illnesses and increased mortality, especially among vulnerable populations (Rohini et al., 2016) Crop yield losses and livestock productivity declines (Chand et al., 2021)

07.	Industrial Processes	Industrial operations of cement production, chemical manufacturing etc. release GHGs (IPCC, 2014b).	Release of GHGs, such as carbon dioxide and hydrofluorocarbons (IPCC, 2014b) Air and water pollution from industrial waste and emissions (Worrell et al., 2001)
08.	Increasing Population and Urbanization	The growing global population and urbanization lead to increased energy demand, transportation needs, and waste generation, contributing to GHGs (Seto et al., 2014).	Increased energy demand and resource consumption (Seto et al., 2014) Urban heat island effect and air pollution (Grimmond, 2007)
09.	Coastal Flooding and Erosion	Sea-level rise and severe weather events have led to increased coastal flooding and erosion along India's coastlines, threatening coastal communities and infrastructure (Kumar and Tholkappian, 2019).	Displacement of coastal communities and loss of infrastructure (Kumar & Tholkappian, 2019) Damage to coastal ecosystems, such as mangroves and coral reefs (Spalding et al., 2014)
10.	Changing Rainfall Patterns	Climate change has altered rainfall patterns in India, leading to more frequent droughts and floods, affecting agriculture, water resources, and livelihoods (Nandargi and Dhar, 2012).	Water scarcity and drought conditions, affecting agricultural production (Nandargi & Dhar, 2012) Increased risk of floods and landslides, causing damage to property and loss of life (Hirabayashi et al., 2013)
11.	Biodiversity Loss:	Climate change is contributing to the loss of biodiversity in India, with species facing habitat loss, changes in migration patterns, and increased extinction risks (Chaudhary and Bawa, 2020).	Species extinctions, such as the Critically Endangered Pygmy Hog (Porcula salvania) due to habitat loss (Chaudhary & Bawa, 2020) Disruption of ecosystems and their services, including pollination and pest control (Chapin et al., 2000)
12.	Risk of Lower Agricultural Production and food security	The influence of climate change on Indian agriculture is profoundly significant (Shiva, 2010). With 62% of cultivated land still reliant on rainfall, as documented by the Ministry of Environment and Forests in 2002, the agricultural sector in India	According to reports, approximately 150,000 Indian farmers took their own lives within a span of nine years from 1997 to 2005. Although farm suicides have been recorded across various states, a staggering two-thirds of these tragedies are concentrated in Maharashtra, Karnataka, Andhra Pradesh,

		remains fundamentally tethered to weather patterns.	Madhya Pradesh, and Kerala, despite these states accounting for only a third of the nation's population, as highlighted by The Hindu in 2007.
13.	Impact on Agricultural Productivity:	Escalating temperatures, shifting precipitation dynamics, and heightened frequency of severe weather phenomena are exerting detrimental effects on agricultural yields in India (Chand et al., 2021).	Reduced crop yields, particularly for wheat, rice, and pulses (Chand et al., 2021) Increased pest and disease incidence, affecting crop health (Chakraborty & Newton, 2011)

4. India's Plan for Climate Change Mitigation

To mitigate the impacts of climate change driven by high GHG emissions, renewable energy sources hold significant potential for replacing fossil fuels in electricity generation. This transition plays a vital role in reducing GHG emissions and combating climate change (Edenhofer et al., 2011). However, reducing these emissions is quite challenging given that around 16 million people in India still lack access to electricity (IEA, 2022), highlighting the ongoing need for equitable development and energy access. Sharma et al. (2020) emphasize the perspectives of developing nations on justice, advocating for the fair distribution of mitigation responsibilities alongside considerations of efficiency and cost-effectiveness. Additionally, Halsnaes and Shukla (2008) explore international cooperative mechanisms and financing strategies to support climate mitigation policies in developing countries.

Table 2 presents different plans for mitigation of climate change impacts in India. The aim of these plans is to address the challenges posed by climate change through legislative and policy initiatives. For instance, India's first National Action Plan on Climate Change (NAPCC) launched on June 30, 2008 outlines the current and future strategies for climate mitigation and adaptation. The plan includes eight national missions: the National Solar Mission, the National Mission for Enhanced Energy Efficiency, the National Mission on Sustainable Habitat, the National Water Mission, the National Mission for Sustaining the Himalayan Ecosystem, the National Mission for Sustainable Agriculture, the National Mission for a Green India, and the National Mission on Strategic Knowledge for Climate Change. Among these, the Jawaharlal Nehru National Solar Mission plays a pivotal role. This mission is supported by the Renewable Energy Procurement Obligation (RPO), which was amended under the National Tariff Policy in 2011 to increase the solar-specific RPO from 0.25% in 2012 to 3% by 2022.

The Energy Conservation Act of 2001 introduced mandatory measures like the energy conservation building code for commercial buildings, energy audits for energy-intensive industries, demand-side management initiatives, and industrial energy benchmarking (MoP, 2001). The Electricity Act of 2003, the National Electricity Policy of 2005, and the Tariff Policy of 2006 encouraged the production and procurement of power from non-conventional and renewable sources. The National Rural Electrification Policies of 2006 aimed to provide off-grid renewable power to remote areas (MNRE, 2011). Similarly, the Integrated Energy Policy (2006) emphasized energy efficiency and the promotion of renewable energy (IEP, 2006).

India has committed to voluntary climate action through its Nationally Appropriate Mitigation Actions (NAMAs). The NAMAs target a 20-25% reduction in the GHG intensity of GDP from 2005 levels by 2020 (UNFCCC, 2010). This commitment was further reinforced in India's Intended Nationally Determined Contribution (INDC), submitted on October 1, 2015. India pledged to derive 40% of its power generation capacity from non-fossil fuel sources and reduce emissions intensity by 33-35% from 2005 levels by 2030 (UNFCCC, 2015). To support these goals, platforms like the Akshay Urja Portal and the India Renewable Idea Exchange (IRIX) Portal foster the exchange of environmentally sustainable ideas and promote global collaboration on renewable energy advancements. These comprehensive efforts underscore India's proactive approach to achieving a sustainable energy future while addressing climate change.

Table 2-India's plan for climate change mitigation

S. No	Plan and year	Specification
01.	National Action Plan on Climate Change (NAPCC, 2008)	Outlined eight national duties to address climate change (MOEF, 2010). Focused on enhanced energy efficiency, sustainable habitats, water conservation, and increasing forest cover.
02.	National Mission for Enhanced Energy Efficiency (NMEEE) - 2008	Part of the NAPCC Aimed to achieve energy efficiency through various policies and programs.
03.	Jawaharlal Nehru National Solar Mission (JNNSM) - 2010	Part of NAPCC Aimed to promote solar energy and increase its share in energy mix. Target of deploying 20 GW of grid-connected solar power by 2022.
04.	National Mission for Sustainable Agriculture (NMSA) - 2010	Part of NAPCC Focused on promoting sustainable agriculture practices to adapt to climate change
05.	National Mission on Strategic Knowledge for Climate Change (NMSKCC) - 2010	Part of NAPCC Aimed to build a knowledge network and support research on climate change
06.	Intended Nationally Determined Contribution (INDC) - 2015	Indian commitments under the Paris Agreement. sought to reduce the emissions from 2005 by 33-35% through 2030 achieve about 40% cumulative electric power installed capacity from non-fossiliferous resources by 2030
07.	National Clean Air Programme (NCAP) - 2019	Aimed to reduce particulate matter emissions by 20-30% by 2024 across 122 non-attainment cities
08.	India Cooling Action Plan (ICAP) - 2019	Aimed to reduce cooling demand, enhance energy efficiency, and reduce GHG emissions from the cooling sector.

09.	National Electricity Mobility Mission Plan (NEMMP) - 2020	Aimed to promote electric mobility and increase the adoption of electric vehicles. targets a 30% market penetration in sales of electric vehicles by 2030.
10.	Updated Nationally Determined Contribution (NDC) - 2022	NDC target updation of India under the Paris Agreement. achieve about 50% cumulative electric power installed capacity through non-fossiliferous sources by 2030 Targeted to reduce the emissions from 2005 levels by 45% through 2030.

5. Role of SDGs in Combatting Climate Change

To achieve sustainability, it is imperative to identify crucial component systems and establish indicators that offer essential and dependable insights into the viability of each system and the overall structure. Sustainability involves maintaining the core identity of a system amidst continual change, fostering dynamic interactions with its external environment (Gallopin, 2003). It is not merely a characteristic but a continual process of positive change, enhancing the system over time in a sustainable manner (Gallopin, 2003). When sustainability is coupled with development, it necessitates addressing the key issues vital to human progress (Markandya et al., 2002). Economic development is sustainable if, in relation to its population, a society's productive foundation does not dwindle (Dasgupta, 2007b). Energy savings, efficiency improvements and substitutes of fossil fuels are three major technological changes involved in sustainable development. An example of this approach is the concept of solar cities, which aim to develop economically and environmentally sustainable energy systems. These cities address challenges such as limited financial resources, workforce constraints, and uncertainty about future economic and technological developments. The operationalization of sustainability policies often involves addressing the sustainability of what and whom, leading to a high degree of conflict in sustainability issues (Munda, 2008).

Several researchers have described the role of SDGs in combatting climate change. Fujimori introduced a new concept known as marginal SDG-emissions-reduction values (MSVs) which measure the incremental effects on SDG indicators from each unit of CO_2 emissions reduced. The authors observed significant correlations between CO_2 emission reductions and several SDG objectives. For example, cutting CO_2 emissions by 1% could lead to a 0.57% decrease in premature deaths due to air pollution (SDG 3) and a 0.026% decrease in mean species richness (SDG 15). According to Soergel et al. (2021), despite current initiatives, the efforts in different regions of the world are insufficient to meet the SDG targets. Wu et al. (2021) analyzed the impact of cleaner environment in boosting the economic output of E7 and G7 nations over time while minimizing environmental pollution and transitioning to green and innovative energy sources. Liu et al. (2023) explored the relationship between CO_2 emissions, economic growth, and employment composition in 297 Chinese cities using machine learning. The authors argue that manufacturing and construction industries can achieve this decoupling while also leading to job creation. India is presently prioritizing two key Sustainable Development Goals: SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action).

SDG7 (Affordable and Clean Energy): SDG 7 aims to provide access to affordable, reliable, sustainable, and modern energy for all. In India, this involves promoting the use of renewable energy sources like solar, wind, and hydropower, decreasing dependency on fossil fuels, and enhancing energy efficiency. India is contributing to reducing GHG emissions through substantial investments in clean energy technologies. India has made substantial progress in increasing access to electricity. As of January 2023, over 99% of Indian villages were electrified. The "Saubhagya" scheme, launched in 2017, aimed to provide electricity connections to all households in the country. Due to high demand for electricity, India has set ambitious goals for its renewable energy capacity, aiming for 175 GW by 2022 and 500 GW by 2030.

SDG 13 (Climate Action): SDG 13 directly addresses climate change and its impacts. India has committed on various international fora to reducing its emissions and enhancing its resilience to climate change through different initiatives, including the National Action Plan on Climate Change (NAPCC) and the development of a National Mission on Enhanced Energy Efficiency. India has been making significant progress in the installation of renewable energy plants. India has set a goal to reach a renewable energy capacity of 500 GW by the year 2030. This includes solar, wind, and hydroelectric power, with substantial investments and initiatives to promote these technologies. India has launched initiatives like the Green India Mission and afforestation programs to increase forest and tree cover, thereby contributing to climate change mitigation through carbon sequestration. India has taken measures to address air pollution, which is closely related to climate change. India has been focusing on reducing air pollution from the transportation sector through promoting electric vehicles (EVs) and improving public transportation systems. Initiatives like the National Clean Air Program (NCAP) aim to improve air quality and reduce emissions of air pollutants.

6. Status of Renewable Energy Development

India’s open access renewable energy growth is shown in Figure 1 It can be seen from Figure 1 that there is a clear upward trend in open access renewable energy capacity over the years. Beginning in FY2017, the Indian renewable energy market experienced a strong annual increase in capacity addition. The year FY-2018 marked the peak of this trend with the installation of 2894 MW, the highest annual capacity addition to date. The addition of 3640 MW during FY23 indicates a continued strong growth in open access renewable energy capacity during the period from FY16 to FY23.

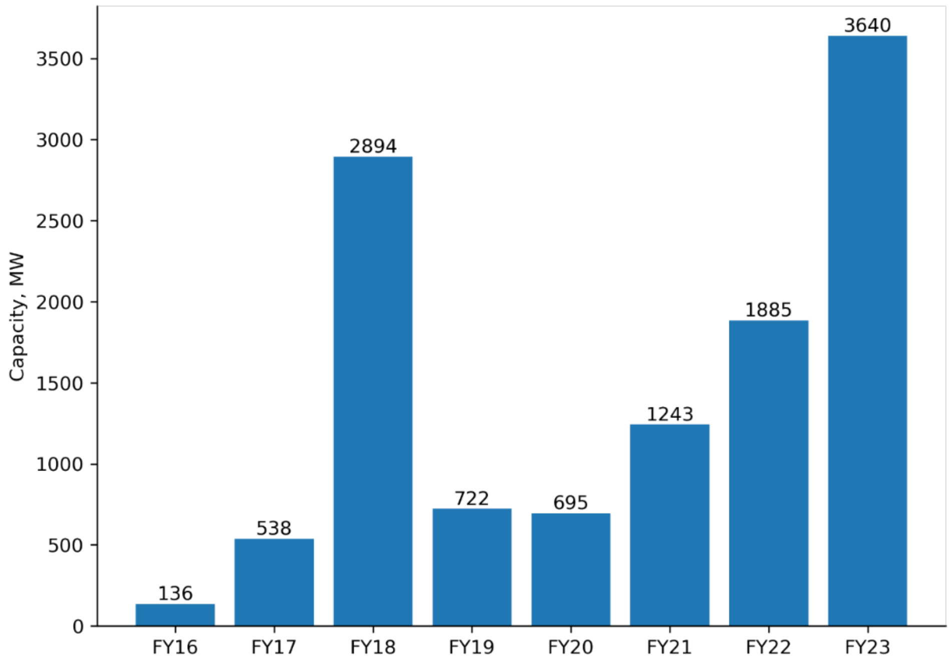

Figure 1 India's open access renewable energy growth (Source: Gulia and Garg, 2022)

Solar Energy

The installed solar capacity in India has seen a massive increase from 40 MW in 2011-12 FY to 81810 MW in 2023-24 FY (Figure 3), making India the 4th largest country globally in terms of solar power capacity. The Solar Park Scheme initiated by the GOI aims to establish 50 solar parks with a cumulative capacity of around 38 GW by 2025-26. Till the end of 2024, 11 parks with a capacity of 8521 MW have been completed. The PM-KUSUM scheme is set to add 30.8 GW by March 2026, focusing on agricultural sector transformation by setting up decentralized solar power plants. The International Solar Alliance of India focuses on enhancing the widespread adoption of solar technologies. India's 2030 vision includes ambitious targets such as achieving 500 GW of renewable energy capacity and reducing carbon emissions by 1 billion tons. India aims for 90% of its energy to be from renewable sources by 2047.

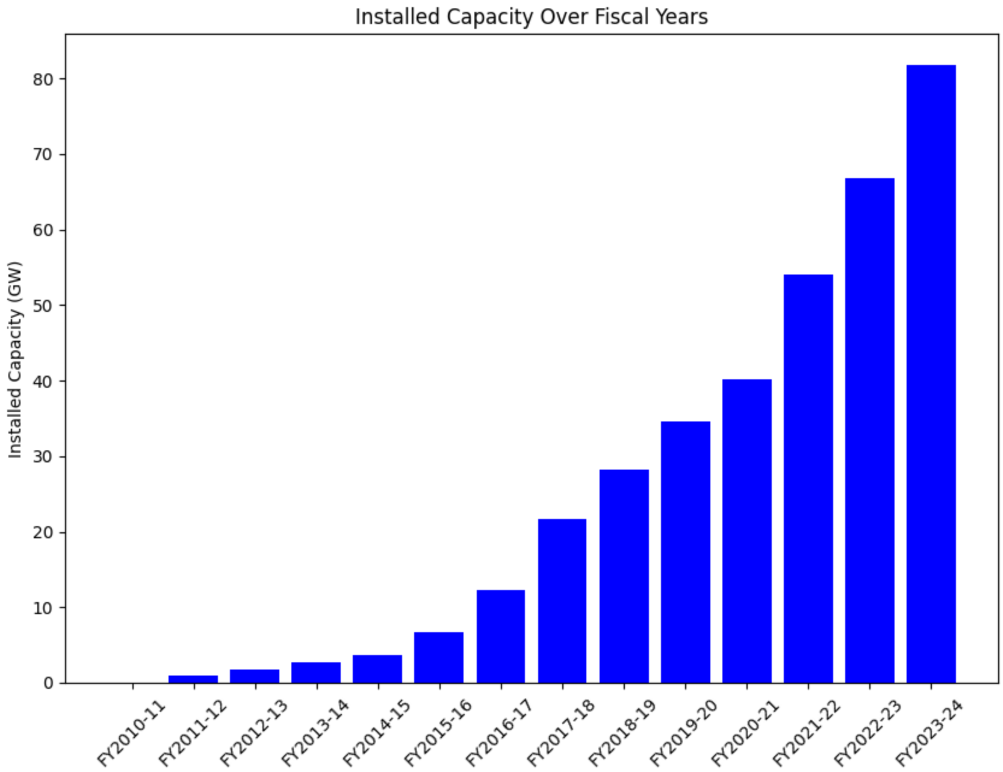

Figure 2 Solar energy capacity in India from FY 2010-11 to FY 2023-24 (Source: NITI Aayog, 2024, India's Climate and Energy Dashboard)

Table 3 Installed solar power capacity in various states

State	**Installed Capacity, MW**
Rajasthan	18,089.21
Gujarat	10,417.56
Karnataka	9,347.18
Tamil Nadu	7,164.59
Telangana	4,712.98
Andhra Pradesh	4,555.20
Madhya Pradesh	3,167.92
Maharashtra	5,064.46
Uttar Pradesh	2,632.61
Punjab	1,266.55

Haryana	1,224.30
Kerala	858.68
Uttarakhand	575.53
Chhattisgarh	1,015.24
Odisha	465.23
West Bengal	194.06
Bihar	223.54
Jharkhand	121.77
Assam	155.81
Himachal Pradesh	111.55
Delhi	236.41
Jammu & Kashmir	54.98
Goa	35.76
Tripura	18.47
Meghalaya	4.19
Manipur	13.03
Nagaland	3.04
Sikkim	4.69
Mizoram	30.43
Arunachal Pradesh	11.79
Ladakh	7.80
Andaman & Nicobar Islands	29.91
Chandigarh	64.05
Dadra & Nagar Haveli and Daman & Diu	46.47
Lakshadweep	4.77
Puducherry	43.27
Others	45.01
Total	72,020.00

Source: CEA (2023)

Table 4 shows installed capacity in different states and union territories. Rajasthan – a northwest province of India possesses significant solar energy potential and has already made strides by establishing expansive solar parks like the renowned Bhadla solar park, recognized as one of the world's largest (Ministry of New and Renewable Energy, GOI, 2022). Rajasthan contributes nearly 25% (18089.21 MW) of India's total installed solar capacity. This significant contribution can be attributed to its vast arid land, high solar irradiance, and favorable government policies for large-scale solar parks. Gujarat ranks second with 10,417.56 MW, mainly due to strong government initiatives like the Gujarat Solar Policy and a robust rooftop solar program. The grid infrastructure and innovative models, such as solar-wind hybrid projects, support the solar capacity in the state of Gujarat. The state of Karnataka has the third largest capacity (9,347.18 MW) owing to early investments in solar parks and rooftop solar installations. The north-eastern states such as Meghalaya (4.19 MW), Nagaland (3.04 MW), and Arunachal Pradesh (11.79 MW) have minimal contributions due to geographical and infrastructural challenges. The Union Territories like Lakshadweep (4.77 MW) and Andaman & Nicobar Islands (29.91 MW) rely on smaller, decentralized solar solutions tailored to their unique energy needs.

Wind Energy

The GOI established a National Offshore Wind Energy Policy in October 2015 that aims to harness offshore wind energy within the Indian Exclusive Economic Zone (EEZ) along its coastlines. As of FY 2023-24, India's wind energy capacity stood at 45.89 GW, placing it as the fourth largest in the world. A target of 140 GW of installed wind capacity by 2030 has been set by India. The National Institute of Wind Energy (NIWE), under the directive of the GOI has set up over 900 monitoring stations nationwide and provided wind potential maps at various heights. Recent data shows a gross potential of 695.5 GW at 120 meters and 1163.9 GW at 150 meters above ground, predominantly across eight windy states. With a potential of 695.5 GW at 120 m height and 1163.9 GW at 150 m height, the target of 140 GW of installed wind capacity by 2030 is quite achievable. The progress in installed wind capacity over different years is shown in Figure 3.

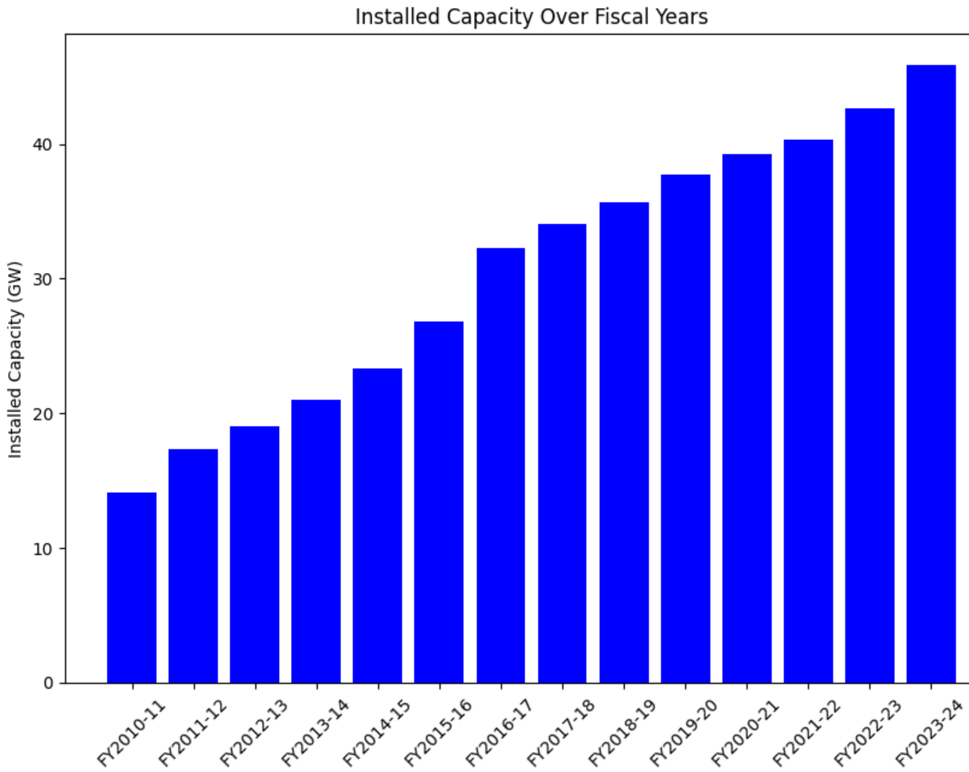

Figure 3 Wind energy capacity in India for FY 2010-11 to FY 2023-24 (Source: NITI Aayog, 2024, India's Climate and Energy Dashboard)

The distribution of total installed wind capacity across various states is shown in Table 4. It can be seen from Table 4 that state of Gujarat has the highest installed capacity, followed closely by Tamil Nadu. The states of Gujarat and Tamil Nadu together account for nearly half of India's total wind power capacity. The significant contributions from Karnataka, Maharashtra, Rajasthan, and Andhra Pradesh further underscore the widespread adoption of wind energy across the country. As of September 30, 2024, India's total installed wind power capacity reached approximately 47,362.92 MW. States such as Meghalaya (4.19 MW), Nagaland (3.04 MW), and Arunachal Pradesh (11.79 MW) have minimal contributions due to geographical and infrastructural challenges. Union Territories like Lakshadweep (4.77 MW) and Andaman & Nicobar Islands (29.91 MW) rely on smaller, decentralized solar solutions due to their unique energy needs. The data shown in Table 3 clearly indicates India's commitment to expanding its renewable energy infrastructure, aligning with national goals for sustainable development and climate change mitigation.

Table 4 Installed wind capacity in various states

State	Installed Capacity (MW)
Gujarat	12,209.18

Tamil Nadu	11,042.44
Karnataka	6,564.36
Maharashtra	5,214.28
Rajasthan	5,195.82
Andhra Pradesh	4,096.65
Madhya Pradesh	2,844.29
Telangana	128.10
Kerala	63.50
Others	4.30
Total	47,362.92

Hydropower

The transition from coal-based or other fossil fuel-based power generation to hydropower can drastically reduce carbon emissions, aiding India's efforts to meet its climate goals and international commitments. According to the Central Electricity Authority (CEA, 2023), India has harnessed only 29% of its vast 145320 MW hydropower potential. This is in sharp contrast with the United States and European Union, which have harnessed over 80% and 70% of their respective hydropower resources according to the International Hydropower Association. As of 2023-24, the installed capacity for hydroelectric power in India is 46930 MW. It is evident from Figure 4 that there is a steady increase in capacity from 2010 to 2024.

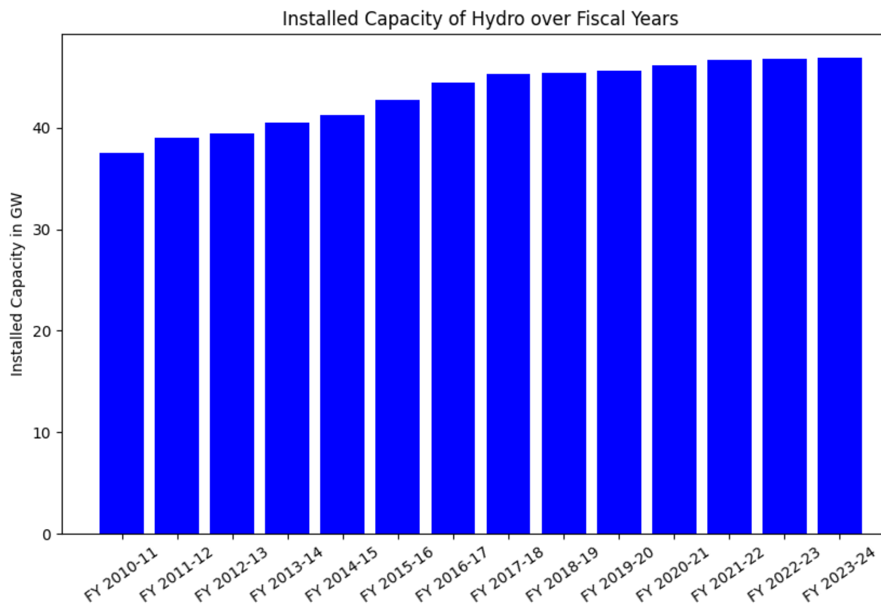

Figure 4 Hydropower capacity in India from FY 2010-11 to FY 2023-24 (Source: NITI Aayog, 2024, India's Climate and Energy Dashboard)

Table 5- State wise distribution of installed hydropower capacity in India

State	**Installed Capacity, MW**
Arunachal Pradesh	405.60
Assam	375.70
Bihar	60.20
Chhattisgarh	120.00
Gujarat	199.00
Himachal Pradesh	10,547.00
Jammu & Kashmir	3,359.00
Jharkhand	130.00
Karnataka	3,793.00
Kerala	2,078.00
Madhya Pradesh	2,435.00
Maharashtra	3,331.00
Manipur	105.00
Meghalaya	356.00
Mizoram	60.00
Nagaland	75.00
Odisha	2,085.00
Punjab	1,045.00
Rajasthan	411.00
Sikkim	610.00
Tamil Nadu	2,321.00
Tripura	16
Uttar Pradesh	547.00
Uttarakhand	3,866.00
West Bengal	1,469.00

Others	1,000.00
Total	46,850.00

Table 5 clearly shows that the state of Himachal Pradesh has the highest installed hydropower capacity at 10,547 MW, accounting for approximately 22.5% of the total capacity in India. The mountainous terrain and perennial rivers like the Sutlej and Beas provide ideal conditions for hydropower generation in Himachal Pradesh. The other three major contributors are Uttarakhand (3,866 MW), Karnataka (3,793 MW), and Jammu & Kashmir (3,359 MW). Together, these states account for nearly 24% of the total hydropower capacity, reflecting their geographical advantages and focus on renewable energy. States in the northeastern parts of India, namely Tripura (16 MW), Nagaland (75 MW), and Mizoram (60 MW) contribute minimally due to either limited infrastructure or untapped potential.

Considerable progress has been made in developing renewable energy sources in India. However, reaching the ambitious target of 500 GW by 2030 remains a formidable challenge. To address this, various initiatives have been implemented to work toward the goal. Table 8 presents the capacity under development for the financial year 2023-24, reflecting an increasing acknowledgment of global environmental concerns and emphasizing the importance of sustainability and environmental preservation.

Table 6-Capacity under development of different energy sources

Source	**Installed Capacity (in GW)**
Solar Under Construction	54.77
Solar Under Development	33.78
Hydro Under Construction	16.74
Hydro Under Construction but stalled	1.24
Wind Under Construction	18.17
Wind Under Development	13.00
Total	137.70448

Table 6 shows the capacity under development for different energy sources. The current installed solar energy capacity stands at approximately 82 GW, with an additional 88 GW in the pipeline. Wind power has an installed capacity of around 46 GW, with 32 GW under development. For hydropower, the installed capacity is 48 GW, while 18 GW is in the pipeline. This data clearly demonstrates the dominant position of solar energy in the renewable energy sector, contributing over 50% of India's 2030 renewable energy target. This emphasis reflects India's strategic focus on utilizing its abundant solar potential. In contrast, wind energy is advancing at a more gradual pace and will require substantial policy support to reach its full potential, particularly in high-wind states such as Gujarat and Tamil Nadu. The growth of hydropower capacity development has been relatively limited due to challenges like long gestation periods, environmental concerns, and community displacement. Overcoming these hurdles is essential to achieving further progress in the hydropower sector.

Central core of sustainable development is the incorporation of economic, social, and environmental considerations into policy formulation. Approaching the issue of climate change through the lens of sustainable development may offer valuable insights and strategies for addressing this pressing challenge (Soltau, 2006). The SDG-7 aims at cheap, reliable, sustainable, and modern energy access to all, which is a key component in climate change mitigation.

7. Challenges and Innovative Solutions

India aims to achieve a renewable energy capacity of 500 GW by 2030, but several challenges must be addressed to achieve this ambitious goal.

1. Infrastructure and Grid Integration: Generation of solar and wind energy is dependent on weather conditions, thereby creating challenges for grid stability and reliability. Therefore, transmission and distribution infrastructure require significant upgrades to handle the increased load from renewable sources. To mitigate intermittency, large-scale deployment of storage solutions like batteries and pumped hydro is essential. However, these technologies remain costly.

2. Land Acquisition and Availability: Solar farms and wind parks require vast areas, often competing with agricultural and forested lands. Acquiring land for large-scale renewable projects can lead to disputes, displacement of communities, and delays.

3. Financing and Investment: Despite declining costs, renewable energy projects still require significant initial investments. Owing to inconsistent and frequent policy revisions, small and medium developers often face challenges in accessing affordable financing.

4. Technological Barriers: Integrating high levels of renewable energy into the grid requires advanced forecasting, demand management, and smart grid technologies. Therefore, developing cost-effective, large-scale energy storage systems remains a significant technological challenge.

5. Dependence on Imports: India relies heavily on imports for critical components like solar cells and modules, primarily from China. Global supply chain issues caused by pandemic or geopolitical tensions can delay project execution.

Some other countries that face similar challenges as India include China, Brazil and South Africa among others. China is a global leader in solar energy manufacturing, accounting for over 70% of the world's solar panel production. China has overcome the challenges of cost effectiveness by scaling production capacity of solar power equipment. The Chinese government introduced initiatives such as the Golden Sun Program and Top Runner Program to promote domestic solar adoption and innovation. Additionally, investment in research and development expenditure has led to improvements in solar cell efficiency and reduced manufacturing costs in the country. Brazil has successfully integrated bioenergy into its renewable energy portfolio, largely through its robust ethanol and biomass programs. Brazil is a global leader in ethanol production, primarily derived from sugar cane. The Proálcool Program, launched in the 1970s, promoted ethanol as a fuel alternative, reducing dependence on imported oil. Over 80% of Brazil's light vehicle fleet run on mixture of ethanol and gasoline. In India, less than 20% ethanol is blended with petrol. However, the National Policy on Biofuels–2018 has set a target of achieving 20% ethanol blending in petrol by 2030. South Africa has a model renewal energy promotion programme known as Renewable Energy Independent Power Producer Procurement Programme (REIPPPP). Under REIPPPP, independent power producers (IPPs) are encouraged to bid for renewable energy projects, creating a competitive and transparent procurement process. The program has attracted significant foreign investment, bringing over USD 14 billion into South Africa's renewable energy sector. As a result, thousands of jobs have been created in the renewable energy sector, leading to significant rural economic development.

To achieve the ambitious renewable energy target of 500 GW by 2030, India must adopt a range of innovative solutions that address technological, financial, and infrastructural challenges. The following key innovative solutions are recommended to achieve the ambitious target of 500 GW by 2030.

1. Advanced Energy Storage Technologies: Large scale investment in lithium-ion, sodium-ion, and flow batteries is required to store surplus energy from solar and wind projects
2. Smart Grid Infrastructure: Smart power grids with advanced monitoring, forecasting, and demand-response technologies are urgently required to manage variable renewable energy efficiently
3. Offshore Wind and Hybrid Renewable Projects: India has a 7500 km coastline that can be utilized for developing offshore wind energy projects. To optimize land use and ensure continuous power supply, policy makers should aim at developing combined solar and wind energy parks
4. Innovations in Solar Energy: Deployment of bifacial solar panels that capture sunlight on both sides can enhance energy output. Additionally, canals and reservoirs can be utilized for floating solar projects
5. Policy and Financing Innovations: To attract domestic and international investors, greater mobilization of funds for renewable energy projects through green bonds and crowdfunding platforms is required

8. Conclusions

India's immense potential in solar, wind, and hydropower offers significant opportunities to mitigate the impacts of climate change and drive sustainable development. Realizing this potential requires overcoming technological, financial, and policy barriers through strategies that minimize environmental impacts, address climate change, and enhance resilience against environmental disruptions. Over the past decade, notable progress has been achieved in enhancing installed capacities across solar, wind, biopower, and hydropower sectors. The initiatives such as the Solar Park Scheme and the PM-KUSUM scheme has led to significant growth, establishing India as a global leader in solar capacity. Wind energy, supported by the National Offshore Wind Energy Policy, has also seen significant advancements, with ambitious targets set for 2030. However, hydropower remains underutilized despite its potential, offering untapped opportunities for reducing emissions.

The installed solar capacity in India stands at 82 GW, with an additional 88 GW under development. Wind energy has an installed capacity of approximately 46 GW, with 32 GW in the pipeline. Hydropower contributes around 47 GW of installed capacity, and around 18 GW is under development. Collectively, India currently has about 175 GW of renewable energy capacity. Despite these successes, India faces considerable challenges in achieving its renewable energy target of 500 GW by 2030. This is mainly due to the formulating effective climate change mitigation policies that necessitate balancing international commitments with domestic developmental needs. Additionally, GHG emissions from fuel combustion and thermal power plants remain inevitable by-products of economic and infrastructure development. Therefore, innovative solutions, robust policy frameworks, and sustained investments in renewable energy are required to secure a sustainable and resilient energy future.

Renewable energy development offers a comprehensive and sustainable solution to address the dual challenge of mitigating climate change and meeting India's energy needs. By replacing fossil fuels with solar, wind, hydropower, and bioenergy, India can significantly lower its carbon footprint and move closer to achieving its commitments under the Paris Agreement. Additionally, renewable energy development would contribute to improved air quality by reducing harmful pollutants such as sulfur dioxide, nitrogen oxides, and particulate matter. This not only addresses public health concerns but also helps mitigate the economic costs associated with air pollution-related illnesses. The transition to renewable energy also supports Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), fostering inclusive and sustainable growth. Renewable energy enables India to enhance its energy security by reducing dependence on imported fossil fuels. Moreover, the sector creates significant economic opportunities, including job creation across different sectors. To maximize these benefits, India must continue to invest strategically in renewable energy infrastructure, innovation, and research. By doing so, renewable energy can become the cornerstone of India's climate change mitigation strategy, ensuring a sustainable, resilient, and prosperous future.

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