An Investigation on the Prospects, Challenges and Policy Consequences of Renewable Energy Technology Development for India's Environmental Sustainability

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Abstract: - This study aims to comprehensively analyze the status and prospects of renewable energies in India. India ranks third globally in terms of renewable energy production. India's population and economic growth are fueling increasing energy demand. Renewable energy has emerged as a viable solution for addressing the energy crisis and environmental issues, replacing fossil fuels. The Indian government is actively promoting and pursuing large-scale renewable energy projects as part of its commitment to increase the utilization of renewable energies. This paper analyzes the complexities of India's renewable energy industry, focusing on its substantial growth and the government's proactive efforts to promote a greener energy mix. By 2023, renewable energy sources constituted over 40% of India's overall energy capacity, amounting to approximately 169 GW. The figure comprises 64 GW of solar electricity, 52 GW of hydropower, 42 GW of wind energy, and 11 GW of biofuels. Rajasthan possesses the greatest potential for renewable energy in India, representing approximately 20% of the nation's overall capacity. The article explores the interdependent relationship between renewable energies and Sustainable Development Goals (SDGs), such as poverty reduction, gender equality, improved health, and environmental preservation. The research not only presents empirical data on India's renewable energy capabilities but also offers policy recommendations to facilitate a transition from fossil fuels to renewable energies. These recommendations address economic, social, and environmental aspects. The article outlines a strategic plan for India's sustainable energy future, emphasizing the importance of robust government regulations, private sector investments, international collaboration, and public awareness initiatives. This study contributes to the ongoing discussion on renewable energy adoption in India by providing a strategic and practical framework. This study provides valuable insights for policymakers, researchers, and industry competitors regarding energy transition and environmental sustainability.

Key-Words: - Renewable energy, Environmental sustainability, Climate change, Energy transition, Emission reduction, Sustainable development goal, Energy policy, India.

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1 Introduction

In India, the increasing population and expanding economy are driving up the energy demand. This is a challenge to fulfill this requirement while also addressing environmental considerations. Renewable energy has become a vital participant in India's pursuit of a sustainable and environmentally friendly energy solution. As the global population expands, there is a corresponding rise in the need for energy to converge with the expanding demand for electricity in residential, commercial, and communal settings, [1]. Since the Industrial Revolution, several nations have relied more on fossil fuels for energy sources (coal, oil, gas). The phenomena affect global climate and human health, [2]. One of the most significant issues of concern in the 21st century is global warming and climate change, mostly attributed to greenhouse gas (GHG) emissions due to the increased utilization of fossil fuels, [3]. Approximately 75% of worldwide GHG emissions are attributed to the combustion of fossil fuels for energy production, [4]. Fossil fuels are accountable for significant levels of localized air pollution, which poses a health concern resulting in a minimum of 5 million premature fatalities annually, [5]. To cut emissions and mitigate the adverse effects of local air pollution, there is an urgent global imperative to transition expeditiously towards energy sources characterized by low carbon emissions, such as nuclear and renewable technologies, [6]. The development and proliferation of renewable energies play a crucial role in upholding sustainable energy levels and safeguarding the environment against the effects of climate change, [7]. The present world is confronted with the dual imperative of meeting the escalating energy requirements and mitigating GHG emissions while enhancing energy efficiency, [8]. Renewable energy offers an effective solution to the pressing challenge of meeting energy demands while reducing emissions, [9]. Furthermore, it is crucial to note that this factor also assumes a significant part in the realm of energy security, in addition to the enhancement of environmental preservation and the augmentation of employment opportunities throughout diverse nations, [10]. Thus, renewable energy sources are currently of great interest to nations worldwide due to their pollution-free nature, widespread availability, cost-effectiveness, and abundant reserves on Earth, [11]. Renewable energy technology necessitates the utilization of naturally occurring energy resources, for instance, solar radiation, wind, water, biomass, and geothermal energy, among others, [12]. Renewable energy is widely recognized by numerous countries as a pivotal and influential aspect of the latest energy technological advancements, [13]. Consequently, these governments have established ambitious objectives for renewable energy as an integral component of their policy frameworks, [14]. The significance of low-carbon development has become increasingly crucial due to the progress in national policies and the advancement of renewable energy technologies, [15]. Recently, there has been more focus on the utilization of clean energy sources for attaining the sustainable development goals (SDGs) proposed by the United Nations that serve as a blueprint for the advancement of global human well-being, material conditions, and the preservation of the natural environment, with a projected timeline of achievement by the year 2030.

Moreover, by 2022, renewable energy sources had contributed to about 30% of the total worldwide electricity generation, marking a significant 10 percentage point rise compared to the year 2010, [16]. The rise of renewable energy was supported by long-term contractual agreements, granting first dibs on the electricity grid, and the ongoing establishment of newfangled power plants, [17]. These factors remained influential despite reduced electricity demand, issues in the supply chain, and construction delays observed in various regions globally. The International Energy Agency (IEA) predicts that by 2028, renewable energy sources will provide 42% of the world's electrical supply, with wind and solar power accounting for 25% of that total, [18]. This anticipated increase represents the most rapid when compared to the expansion observed since the 1970s, [19]. China is projected to provide over 50% of the worldwide growth in renewable electricity in the year 2021, with the United States, the European Union, and India following suit, [20]. In 2021, the total global cumulative capacity of solar PV reached 940 GW, accompanied by the installation of around 168 GW of additional PV capacity during the same year, or an approximate growth of 18%, [21]. China is predicted to hold its rank as the largest market for PV technology, while the United States is anticipated to experience further growth because of sustained legislative backing from both federal and state governments. Wind energy is projected to see the most substantial growth in renewable generation, with an estimated rise of 275 TWh, equivalent to over 17%, [22]. This growth is much higher compared to the levels observed in 2020. In the upcoming years, it is projected that China will produce 600 TWh of wind energy, while the United States is anticipated to generate 400 TWh, [23]. Collectively, these figures account for a significant portion exceeding fifty percent of the total world wind energy output. It is anticipated that there will be a notable rise in hydropower generation in the year 2021. In addition, the rise of bioenergy in Asia is expected to be driven by energy from waste power projects, mostly because of the presence of incentives, [22]. The anticipated growth in power generation derived from various renewable sources is expected to result in a substantial increase in the share of renewables in the mix of energy sources used to generate power, reaching an unprecedented peak of 30% in the year 2021, [24]. In the year 2021, the collective energy production from nuclear power and other low-carbon sources has surpassed the total output generated by coal plants worldwide. The IEA predicts that this proportion will increase to 30% by the year 2024, [25].

However, India is currently ranked as the third largest user of power globally, as well as the third greatest producer of renewable energies, [26]. The use and expansion of renewable energies in India have made great strides in recent years, [22]. When compared to other countries, India's installed capacity for renewable energies is the fourth highest in the world, [22]. In the year 2022, over 40% of the total energy capacity, amounting to almost 163 GW out of 400 GW, came from renewables, [27]. The imperative to shift from fossil fuel-dependent energy systems to more environmentally friendly and sustainable substitutes is widely acknowledged throughout the nation. The Indian government has demonstrated a robust dedication to the progression of renewable energies, [28]. India, following the targets outlined in the Paris Agreement's Intended Nationally Determined Contributions for the year 2016, pledged to produce 50% of its overall electricity from non-fossil fuel sources by the year 2030. India is currently undergoing a substantial expansion in its renewable energy industry, intending to attain a capacity of 450 GW by the year 2030, [29]. The nation has enacted laws, rules, and incentives aimed at fostering investments in projects related to renewable energy. Various policy methods like feed-in tariffs, tax inducements, subsidies, and renewable energy goals have been used to stimulate the extension of the renewable energy segment. The Indian government has employed a range of programs and initiatives, including the National Solar Mission, the Renewable Energy Certificate Mechanism, the Wind Power Program, and the Green Energy Corridor Project, intending to promote and incentivize investments in renewable energy ventures, [29]. India is advocating for the implementation of clean energy in countryside regions via several initiatives, including the Deendayal Upadhyaya Gram Jyoti Yojana (DDUGJY) and the Pradhan Mantri Sahaj Bijli Har Ghar Yojana (Saubhagya). These programs are designed to ensure equitable and widespread provision of electricity to every household inside the nation, [22].

Furthermore, India is currently making significant financial commitments toward renewable energy resources, such as solar, wind, and hydropower. As a result, India has emerged as a prominent player in the global renewable energy segment, securing the position of the third-largest solar market and the fourth-largest wind power installed capacity worldwide, [22]. The present circumstances witness the renewable energy industry exerting influence on various aspects of the country, encompassing the augmentation of productivity, attraction of foreign investors, stimulation of domestic investment, amelioration of substandard living conditions, stabilization of policies, promotion of environmental sustainability, and generation of employment opportunities, [30]. Notwithstanding the optimistic viewpoint, India encounters specific obstacles in its endeavor to shift towards renewable energy sources. Some of the factors that contribute to these challenges are a lack of sufficient financial resources, technology limitations, poor grid infrastructure, and gaps in policy implementation, [22]. Successfully addressing these difficulties necessitates the implementation of collaborative approaches, innovative strategies, and the establishment of international cooperation and assistance.

However, while there exists a considerable body of research on the progress of the renewable energy sector in China and the United States, [31], the academic literature concerning India's specific circumstances remains relatively scarce. India, although the third largest market for renewable energy, has a research deficit in its renewable energy industry that has to be addressed to further the development of renewable energy technology in the country. Moreover, it is essential to pinpoint and emphasize the specific areas that require further investigation to gain a deeper understanding of the obstacles and possibilities in India's shift towards renewable energy. This is vital to achieve the Indian government's objective of increasing the country's installed capacity for renewable energies to 500 GW by 2030. Furthermore, it is important to maintain ongoing endeavors to effectively tackle obstacles and guarantee the long-term viability of renewable energy in India. The prospects of India's ability to effectively address energy challenges in the forthcoming decades are contingent upon its receptiveness to global advancements in renewable energy and its capacity to adapt its energy development strategies. India's trajectory for a low-carbon economy aligns with the contemporary imperatives of sustainable economic and social progress. A comprehensive comprehension of both international and domestic policies, legal frameworks, and market mechanisms is crucial in effectively addressing energy-related challenges, devising optimal strategies for renewable energy production and consumption, and ultimately transitioning from a high-carbon to a low-carbon era. Moreover, with the ongoing acceleration of the worldwide movement towards cost-effective, environmentally friendly, and highly productive energy systems, there exists a genuine imperative to augment the comprehensive comprehension of the interconnection between energy and the promotion of sustainable development. Hence, the primary objective of this research is to provide an in-depth review of the status of renewable energy in India and propose a strategic trajectory for renewable energy development policies that can effectively contribute to the attainment of climate goals. This review provides a snapshot of the present state and future potential of renewable energy development in India, encompassing an examination of government policies, challenges, inducements, and the impact of renewable energies on the nation's economic development. Furthermore, this study provides evidence of the potential of renewable energy sector expansion in India to contribute towards the accomplishment of all 17 SDGs outlined by the United Nations. The findings of this research hold the potential to support the formulation and execution of suitable policies targeted at the advancement of India's renewable energy industry. Additionally, these policies can assist in emission reduction and the attainment of climate objectives by stimulating the adoption of renewable energies, ultimately working towards the achievement of the SDGs.

2 Renewable Energies

Renewable energies serve as a viable substitute for conventional energy sources, which heavily depend on fossil fuels, and exhibit a significantly reduced environmental impact, [32]. There exist numerous options to effectuate positive change in environmental improvement by selecting a more sustainable energy solution. The renewable energy sector is experiencing significant growth due to advancements in technology that have resulted in cost reductions and the realization of the anticipated benefits of clean energy, [33]. Figure 1 presents different types of renewable and sustainable energies.

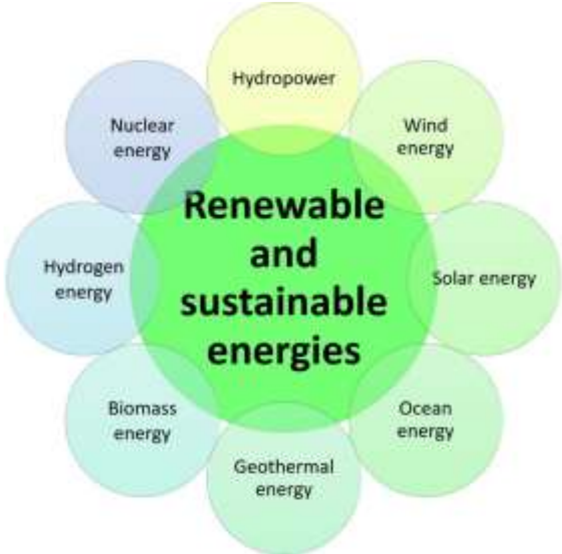

Fig. 1: Different types of renewable and sustainable energies

2.1 Hydropower

On a global scale, it is evident that hydropower is acknowledged as being among the most established and significant supplies of low-carbon energy. The history of large-scale hydroelectric power can be traced back over a century, making it the predominant renewable energy source, [34]. The construction of a dam or barrier enables the establishment of a substantial reservoir, which can be effectively utilized to regulate the flow of water and afterward activate a turbine, facilitating the generation of electrical energy, [35]. The contribution of hydropower beats nuclear power by 55% and surpasses the joint contributions of other renewable energies, for instance, wind, solar, biofuel, and geothermal. Hydroelectricity was responsible for 17% of the world's total electricity output in 2020, positioning it as the third most significant energy source, following coal and natural gas, [36]. In the year 2021, the worldwide installed capacity of hydropower electricity extended over 1400 GW, thereby establishing its position as the most prominent renewable energy technology, [37]. Hydroelectricity assumes a prominent position in nations such as China, Canada, Brazil, the United States, Russia, India, and Norway.

2.2 Wind Energy

Wind energy is a highly abundant and environmentally friendly form of renewable energy. To utilize wind energy for the generation of electricity, turbines are employed to propel generators, subsequently supplying electrical power to the National Grid, [38]. Wind farms have become a progressively more prevalent feature in China, the

United States, Germany, India, Spain, and the United Kingdom, as wind power continues to make a growing contribution to the National Grid. Wind energy is the foremost non-hydro renewable technology, having produced a substantial amount of over 2100 TWh in the year 2022, [39]. The share of global power generation that came from wind energy sources increased significantly in 2022, reaching around 7.33 percent, compared to the share of 6.6 percent that it had in the previous year, [39].

2.3 Solar Energy

Solar radiation is a plentiful and readily accessible energy source on Earth. The solar irradiance received by the Earth's surface within a one-hour time frame exceeds the cumulative energy demands of the globe for an entire year, [40]. Solar energy refers to the radiant energy emitted by the sun, encompassing both electromagnetic radiation and thermal energy. Solar energy is a significant contributor to the renewable energy sector and may be sorted into two groups: active solar energy and passive solar energy. The active technologies encompassed under the realm of solar energy involve PV systems, contemplated solar energy, and solar water heating. The utilization of passive solar approaches encompasses building adjustment, thermal biomass, and natural air passage, [41]. The solar PV sector experienced a notable surge in energy production, with an outstanding gain of 270 TWh in 2022, indicating an extensive growth of 26% in comparison to the year before, [42]. About 4.5% of the world's electricity came from solar PV systems in 2022, making it the third most popular renewable electricity technology after hydropower and wind, [42]. Solar energy is getting popular in China, the United States, India, Brazil, Germany, and Japan, as a means of augmenting their energy use.

2.4 Ocean Energy

Ocean energy encompasses various types of sustainable energy obtained from the marine environment. Ocean energy is characterized by its affordability, widespread accessibility, and environmentally sustainable attributes. There exist three primary categories of ocean energy technology, namely wave energy, tidal energy, and ocean thermal energy, [43]. Tidal energy is a widely recognized form of hydropower that involves the conversion of energy derived from ocean tides into electrical energy. The tidal power is derived from the tidal movements of Earth's oceans. The utilization of tidal streams primarily involves the conversion of the kinetic energy inherent in the movement of water into a viable source of electricity through the operation of turbines, [44]. The utilization of wave and tidal energy constituted nearly 1.5% of the global aggregate installed electricity, 4.5% of the overall capacity of renewable energies, and approximately 7.5% of the aggregate hydropower capacity worldwide, [22].

2.5 Geothermal Energy

Geothermal energy refers to the thermal energy derived from geological sources, which is both spawned and amassed within the Earth. Geothermal energy is dependent on the geothermal gradient, which is determined by the temperature variance between the earth's interior and surface, [45]. Radioactive decay is responsible for the production of the interior heat of the planet. The dissipation of heat is facilitated by the process of fluid circulation, which occurs through many mechanisms such as magma streams, hot springs, or hydrothermal flow. Geothermal energy is a cost-effective, readily accessible, sustainable, reliable, and environmentally friendly form of energy, [46]. Although the initial capital investment is substantial, the ongoing operational expenses are very cheap. Despite the presence of this power source beneath our feet, its overall significance remains limited. Geothermal energy represents a meager 0.5% of the total installed capacity for electricity production, as well as heating and cooling systems, on a global scale, [47]. The countries that produce the most geothermal energy are the United States, Indonesia, Philippines, Turkey, New Zealand, Mexico, Kenya, Italy, and Iceland.

2.6 Biomass Energy

Biomass refers to a sustainable and organic substance derived from living organisms, encompassing both plant and animal sources. Biomass comprises the accumulated chemical energy derived from solar radiation, which is synthesized by plants via the process of photosynthesis, [48]. Biomass offers a more cost-effective and environmentally sustainable means of power generation by utilizing agricultural, industrial, and home waste to produce solid, liquid, and gaseous fuels, [49]. Biomass has the potential to be utilized either by direct combustion for heat generation or by undergoing conversion procedures to produce liquid and gaseous fuels. Biomass can undergo conversion processes that result in the production of energy in the form of methane, ethanol, or biodiesels, [50]. The thermochemical conversion of biomass encompasses two primary processes, namely pyrolysis and gasification. Both thermal decomposition procedures include the heating of biomass feedstock materials enclosed and pressured tanks known as gasifiers, operating at elevated temperatures, [50]. Globally, the total electricity generation from biomass in the year 2020 amounted to 685 TWh. Solid biomass supplies 69% of the total biopower produced, while municipal and industrial waste contributes 17% of the whole biopower production, [22]. In 2019, the continent of Asia was responsible for 39% of the total global biopower generation, amounting to a production of 255 TWh. Following closely behind, Europe accounted for 35% of the global biopower generation, [22].

2.7 Hydrogen Energy

Hydrogen plays a key role in the generation of energy and serves as a potential substitute for fossil fuels. Because of its low environmental impact and simple method of generating power, hydrogen energy is gaining momentum as a potential clean energy resource, [51]. The utilization of hydrogen and hydrogen-derived fuels holds significant potential in the process of decarbonizing sectors that present challenges in reducing emissions, where other alternatives are either lacking or pose implementation difficulties. These sectors include heavy industries and long-distance transport, [51]. Hydrogen has the potential to be utilized as a source of energy in both fuel cells and internal combustion engines. In the realm of hydrogen vehicles, the utilization of hydrogen has commenced in the context of commercial fuel cell vehicles, including passenger automobiles, while its application in fuel cell buses has been established for a considerable duration. Additionally, it finds application as a propellant for spacecraft propulsion systems and is currently being considered for prospective utilization in hydrogen-based aircraft. There has been a notable surge in interest among automakers regarding fuel technology, as they argue that it offers a relatively affordable and secure option for integration into contemporary vehicle designs, particularly in light of the difficulties encountered by electric car manufacturers in recent times. It is projected that hydrogen has the potential to gather around 20% of the global energy demands and create a market valued at approximately US$2.5 trillion by the year 2050, [22].

2.8 Nuclear Energy

Nuclear energy refers to the utilization of nuclear reactions to generate electrical energy. Currently, a large proportion of electricity is spawned by the utilization of nuclear energy, achieved by harnessing the process of nuclear fission involving uranium and plutonium within nuclear power plants, [52]. Nuclear power, in conjunction with hydropower, represents one of the earliest low-carbon energy systems in existence. Nuclear energy is derived from the process of nuclear fission within a reactor, wherein atoms are split to produce thermal energy that is subsequently used to convert water into steam. This steam is then employed to drive a turbine, facilitating the generation of electricity, [53]. About 10 percent of worldwide electricity, or roughly 4% of the global energy mix, comes from nuclear power, which is supplied by nearly 450 reactors in different countries throughout the world, [52]. France, the United States, China, Russia, South Korea, and Canada are significant contributors to the production of nuclear power applications.

3 Present Status of Renewable Energies in India

Achieving sustainable development can be facilitated by the utilization of sustainable energy sources and by guaranteeing equitable access to affordable, dependable, sustainable, and contemporary energy services for all individuals, [54]. India's strong government support and thriving economy have propelled it to the forefront of the renewable energy industry on a global scale. To lure international investments to speed up the country's progress in the renewable energy industry, the government has established legislation and policies and fostered a permissive environment, [55]. There is an expectation that the renewable energy industry will have the potential to generate a significant quantity of domestic employment opportunities in the coming years. Figure 2 presents the annual pattern of renewable energy capacity in India from 2009 to 2023. India possesses a significant abundance of renewable energy resources, as indicated in Table 1.

As of February 2023, the collective installed capacity of renewable energy in the nation of India amounts to 169 GW. Among the aggregate power capacity of 168.96 GW, solar electricity generates 64.38 GW, hydropower constitutes 51.79 GW, wind energy contributes 42.02 GW, and bioenergy represents 10.77 GW. An additional 82.62 GW of renewable energy capacity is currently being implemented, while 40.89 GW of capacity is in different phases of tendering. However, the variability in the accessibility of renewable energy sources around distinctive states in India is evident, [22].

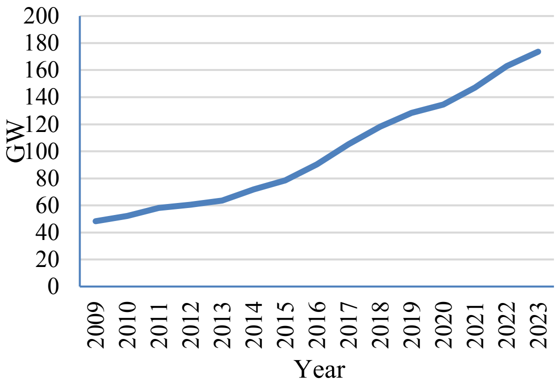

Fig. 2: Annual trend of renewable energy capacity in India, [27]

Table 1. Total renewable energy installed capacity in India in 2023

Type of renewable energy	Total installed capacity (GW)
Solar energy	64.68
Hydropower	51.79
Wind energy	42.02
Bioenergy	10.77
Total	168.96

Rajasthan, one of the states in India, boasts the best ranking in terms of total installed capacity of renewable energy, amounting to a total of 24.46 GW. Gujarat closely trails behind, securing the second spot with a capacity of 21.07 GW, while Karnataka occupies the third position with a capacity of 20.60 GW. Tamil Nadu is ranked fourth with a total installed capacity of 20.35 GW, while Maharashtra is positioned fifth with a capacity of 16.10 GW. The combined installed capacity of renewable energies in India is predominantly concentrated in these five states, representing around 61% of the total.

The Indian government has established specific objectives aimed at mitigating India's overall anticipated carbon emissions by 1 billion metric tons by the year 2030. Additionally, the government aims to decrease the carbon intensity of the nation's economy by less than 45% within the same timeframe. Furthermore, the government has set a long-term goal of reaching net-zero carbon emissions by the year 2070. To support these efforts, the government plans to expand India's installed capacity for renewable energies to 500 GW by 2030. India achieved the third position on a global scale in terms of overall additions to its renewable power capacity, recording a substantial 15.4 GW in 2021. This ranking places India behind China, which added 136 GW, and the United States, which added 43 GW. This nation established the world's first ministry for alternative energy in the early 1980s.

India possesses the fifth-largest hydropower capacity globally and hosts numerous substantial hydroelectric power facilities that produce environmentally friendly and sustainable electricity. India possesses a total of 197 hydroelectric power facilities with nine pumped storage stations. The five leading hydroelectric power plants in the country are in the states of Uttarakhand, Maharashtra, Andhra Pradesh, Himachal Pradesh, and Gujarat. Table 2 presents the hydropower capacity in the five leading hydroelectric power plants in India. In the year 2022, the hydropower capacity, amounting to 46.51 GW, constituted around 11.7 percent of the overall capacity. Approximately 12% of the total power generation for the period of 2020-2021 was derived from hydroelectric sources. However, the estimated hydroelectric power potential of India is 148.7 GW. In 2020, the aggregate hydroelectric power production in India amounted to 156 TWh, with the exclusion of small-scale hydroelectric projects. The whole hydropower potential in India amounts to 660,000 GWh per year, with a significant portion of 540,000 GWh/year (about 79%) remaining untapped. India is positioned as the fourth nation globally in terms of its untapped hydropower potential, following Russia, China, and Canada. Additionally, India ranks fifth in terms of its overall potential, with Brazil surpassing it in this regard. However, Hydropower in India encounters numerous obstacles, such as ecological consequences, land procurement, financial investment, socio-economic disputes, regulatory complications, and rivalry with alternative sustainable technologies.

Table 2. Hydropower capacity in the five leading hydroelectric power plants in India

Hydropower projects	States	Hydropower capacity (GW)
Tehri Hydropower Complex	Uttarakhand	2.40
Koyna Hydroelectric Project	Maharashtra	1.96
Srisailam Dam	Andhra Pradesh	1.67
Nathpa Jhakri Dam	Himachal Pradesh	1.53
Sardar Sarovar Dam	Gujarat	1.45

The wind energy producing capacity in India has had substantial growth in contemporary ages. As of August 31, 2023, the cumulative installed capacity of wind energy amounted to 44 GW, positioning it as the fourth-greatest installed wind energy capacity worldwide after China, the United States, and Germany. Wind power constitutes around 10% of India's aggregate installed efficiency energy production capacity and produced 71.814 TWh during 2022–23, or approximately 4.43% of the overall electricity production. The proliferation of wind energy plants in various parts of India is steadily increasing. Gujarat possesses the greatest installed wind energy capacity, with Tamil Nadu ranking second in this regard. Table 3 presents the installed wind energy production capacity in several states of India in May 2023. Some successful wind farms in India include Pratapgarh Wind Farm in Rajasthan, Rojmal Wind Farm in Maharashtra, Poolavadi Wind Farm in Tamil Nadu, Nimbagallu Wind Farm in Andhra Pradesh, and Samana Wind Farm in Gujarat. However, the wind energy business in India encounters numerous obstacles, including regulatory ambiguity, competitiveness, land accessibility, expenses, technological hurdles, installation prices, maintenance costs, and grid interconnection. Wind energy is confronted with several obstacles such as delays in completing projects, stalling in meeting installation targets, disruptions in supply chains, and changes in state land policy.

The solar power sector in India is seeing rapid growth and development. India possesses a substantial capacity for harnessing solar energy, as the majority of its regions experience more than 300 days of sunshine annually. India now has an installed solar power capacity of 82 GW as of March 31, 2024, which positions it as the third largest solar power generator worldwide after China and the USA.

Table 3. Wind energy generation in different states of India in May 2023

States	Wind energy (MW)
Gujrat	10,415.82
Tamil Nadu	10,124.52
Karnataka	5,303.05
Rajasthan	5,193.42
Maharashtra	5,026.33
Andhra Pradesh	4,096.65
Madhya Pradesh	2,844.29
Telangana	128.10
Kerala	62.50
Others	4.30
Total	43,198.98

Nevertheless, India's present solar energy production falls short of its potential, accounting for less than 10% of the total capacity it might theoretically create. India's objective is to reach a cumulative solar power capacity of 280 GW by the year 2030.

The state-wise capacity of solar energy conversion in India in March 2023 is presented in Table 4. Rajasthan and Gujarat are the leading Indian states in the generation of solar energy. In 2009, the Indian government introduced the Jawaharlal Nehru National Solar Mission intending to generate a range of 1 GW to 20 GW of solar power energy for electricity production. The average daily solar power plant production capacity in India is estimated to be 0.25 kWh/m2 of utilized acreage, [22]. Additionally, the overall solar electricity generation capacity in India is reported to range between 1700 and 1900 kWh per kW. India has approved a total of 45 solar parks, with a combined capacity of 37 GW. The total installed capacity of solar parks in Pavagada is 2 GW, in Kurnool it is 1 GW, and in Bhadla-II it is 648 MW. The solar parks rank within the top five operational solar parks in the nation, boasting a collective capacity of 7 GW. Currently, there is an ongoing project in Gujarat to create a solar-wind hybrid system with a capacity of 30 GW. This initiative aims to establish the largest renewable energy park globally. As of March 2024, India's largest solar power plant is Bhadla Solar Park in Rajasthan. Other large solar parks include Pavagada Solar Park in Karnataka, Kurnool Ultra Mega Solar Park in Andhra Pradesh, NP Kunta Ultra Mega Solar Park in Andhra Pradesh, and Rewa Ultra Mega Solar in Madhya Pradesh. However, India encounters numerous obstacles in its solar energy industry, encompassing issues such as high expenses, limited availability of land, inadequate infrastructure, reliance on imports, insufficient research and development, extended payback periods, air pollution, and inadequate energy storage.

Table 4. Installed solar energy capacity in different states of India in March 2023

States	Solar energy (GW)
Rajasthan	17.06
Gujarat	9.25
Karnataka	8.24
Tamil Nadu	6.74
Telangana	4.67
Andhra Pradesh	4.53
Madhya Pradesh	2.80
Uttar Pradesh	2.52
Punjab	1.17
Haryana	1.03

Moreover, tidal energy is considered a viable and sustainable form of renewable energy. In the context of India, the whole potential capacity of tidal energy is projected to be almost 40 GW. According to the data presented in Table 5, it has been approximated that India has harnessed a total of 8300 MW of tidal energy. Additionally, the proposed energy generation plans encompass a capacity of 7000 MW in the Gulf of Cambay and 1200 MW in the Gulf of Kutch. The Ministry of Renewable Energy offers financial assistance of up to 50% of the expenses incurred by the state Government implementers' agency to implement a tidal energy project. The initial investment required for the installation of a wind energy-producing machine is substantial, but the subsequent operational expenses associated with its maintenance and functioning are comparatively less. India possesses an extensive coastline that encompasses numerous gulfs and estuaries, characterized by robust tidal currents capable of facilitating the generation of power through the utilization of turbines, [56]. However, tidal energy in India encounters numerous obstacles, such as exorbitant expenses, ecological apprehensions, irregular availability, restricted energy consumption, geographical constraints, and equipment maintenance.

Table 5. Tidal energy potential in India

Region	States	Total potential (MW)
Gulf of Cambay	Gujrat	7000
Gulf kutch	Gujrat	1200
Ganges Delta, Sunderban	West Bengal	100

Geothermal energy in India is now in its early developmental phase. At present, the Geological Survey of India has identified over 340 thermal springs throughout the nation, [57]. The primary region harboring geothermal resources is situated within the Himalayas, spanning from Puga in Jammu and Kashmir to Manikaran in Uttar Pradesh, and extending further to Takshing in Arunachal Pradesh. As per the Ministry of New and Renewable Energy (MNRE), a comprehensive mapping of geothermal resources throughout India has been conducted, revealing a potential geothermal power capacity of approximately 10 GW. The Vindhyachal Thermal Power Station, situated in the Singrauli region of Madhya Pradesh, is presently recognized as the biggest thermal power plant in India, boasting an installed capacity of 4.76 GW. Historically, the progress of geothermal energy implementation in India has been constrained by a dearth of technical proficiency and substantial initial expenditures, [57]. Nevertheless, the Indian government has implemented measures to harness this potential by establishing geothermal power facilities and providing incentives to encourage private investment in the industry. The Ministry of Renewable Energy has set a target to produce a maximum of 1000 MW of geothermal energy by the year 2022. However, geothermal energy is limited by the scarcity of suitable sites for exploitation, as well as its distant locations that are typically far from areas where the energy is needed. Additionally, it produces unpleasant gaseous emissions. The development of projects encounters obstacles such as insufficient funding, technological limitations, and lengthy gestation periods ranging from 5 to 10 years for traditional power plants.

Biomass energy is produced in India within the organization for operational needs. Approximately 32% of the nation's primary energy consumption is typically sourced from biomass, while approximately 70% of the population typically relies on this form of energy. The approximate annual biomass availability in India is projected to be around 750 million metric tons. According to the data presented in Table 6, the current biomass energy generation in India is at around 2665 MW. The utilization of biogas in India has a longstanding history. During the 1970s, the nation initiated the National Biogas and Manure Management Program (NBMMP) as a response to the prevailing issue of gas scarcity. The nation conducted extensive studies and employed a diverse range of strategies to enhance the self-reliance of its citizens, irrespective of the accessibility of conventional gasoline and other fossil fuel-derived commodities. In comparison, the generation of biogas in India is rather limited. The current biogas production is approximately 2.07 billion m^3 per year, however, it has been suggested that the potential production might reach up to 48 billion m^3 per year, [58]. Each year, the metropolitan areas of India produce around 55 million tons of municipal solid waste and 38 billion gallons of sewage. According to estimates, the per capita rate of waste generation in India is projected to experience an annual growth of 33%, indicating a huge capacity for biogas production from waste, [22]. India currently holds the second position globally in terms of agricultural biomass generation, with an annual production of approximately 990 million metric tons (MMT) as of May 2024, following China. However, in India, biomass energy has various hurdles, such as regulatory obstacles, seasonal fluctuations in availability, restricted storage options, and transportation limitations. Additional obstacles associated with biomass energy encompass environmental ramifications, rivalry with food cultivation, inefficiency, and financial burden.

Table 6. Biomass energy projects in different states of India

States	Biomass energy generation (MW)
Uttar Pradesh	592.50
Tamil Nadu	488.20
Maharashtra	403.00
Karnataka	365.18
Andhra Pradesh	363.25
Chhattisgarh	231.90
Rajasthan	73.30
Punjab	74.50
Haryana	35.80
West Bengal	16.00
Uttarakhand	10.00
Bihar	9.50
Madhya Pradesh	1.00
Gujarat	0.50
Total	2664.63

Hydrogen-based power generation is considered a form of clean energy that is devoid of pollution. In India, hydrogen energy is commonly employed within the transportation sector to power vehicles. It offers a sustainable and enduring resolution to address the escalating energy requirements in India, while concurrently safeguarding energy sovereignty. There is a significant number of hydrogen-powered cars in India, specifically one million units. This figure encompasses 700,000 two-wheeled vehicles and 50,000 three-wheeled vehicles, [22]. India aspires to establish itself as a prominent global center for the generation of green hydrogen, a process involving the electrolysis of water molecules utilizing renewable energy sources. The proposed strategy is ambitious for a nation that now relies predominantly on fossil fuels to produce hydrogen. India has set a target to achieve a yearly generation of 5 million tons of green hydrogen by the year 2030. This ambitious goal is presumed to result in a drop of around 50 million tons of carbon emissions and generate savings exceeding $12 billion by reducing reliance on fossil fuel imports, [51]. In January 2023, the Indian government sanctioned a financial stimulus package amounting to $2.11 billion to foster the utilization and development of green hydrogen technologies within the country, [51]. By the year 2050, it is projected that the demand for hydrogen in India may experience a significant increase, potentially reaching a five-fold growth. However, India encounters numerous obstacles in its shift towards a hydrogen-centric economy, encompassing factors such as expenses, storage and transportation, infrastructure, demand, and technological capability.

India has implemented a predominantly homegrown nuclear power program. It has been demonstrated that the Indian government is dedicated to expanding its nuclear power capacity as a component of its extensive infrastructure-building initiative. The administration has established lofty objectives to expand nuclear capacity. Nuclear energy constitutes the fifth most significant contributor to India's electrical supply, accounting for around 3% of the nation's total electricity production. India possesses a total of 22 nuclear reactors distributed across 7 power facilities situated around the country, resulting in a cumulative nuclear power generation capacity of 7380 MW. In addition to the existing seven operational nuclear power plants, India is currently in the process of constructing six additional nuclear power stations, which collectively possess a total capacity of 9.4 GW. Furthermore, the nation of India has formulated plans to construct an additional eight nuclear power facilities, boasting a cumulative capacity of 31,000 MW. In April 2023, the Indian government made an official declaration regarding their intentions to augment their nuclear power generation capacity to 22.5 GWe by the year 2031. This ambitious plan aims to ensure that nuclear energy contributes to approximately 9% of India's total electricity production by the year 2047. To effectively mitigate climate-related challenges, it is imperative to adopt a trajectory towards a carbon-neutral future, while concurrently prioritizing the expansion of nuclear energy alongside wind and solar power sources. This collective effort will pave the path for a more promising and sustainable future. However, India's nuclear energy sector encounters numerous obstacles, such as the management of nuclear waste, inadequate capacity, nuclear safety concerns, financial constraints, and difficulties in acquiring land.

However, India is recognized as a significant global consumer of coal, ranking among the greatest consumers worldwide. Furthermore, the country relies on the importation of fossil fuels, which incurs substantial costs, [59]. Hence, it is imperative to identify alternative means of electricity generation. By adopting this approach, the nation would experience a swift and worldwide shift towards renewable energy technology to attain sustainable development and mitigate the risks of severe climate change. In recent years, India has successfully established a sustainable trajectory for its energy provision. The utilization of renewable energies is of utmost importance in ensuring the attainment of sustainable energy with reduced emissions, [60]. India presents a highly favorable prospect for investments in the renewable energy segment, with a substantial sum of $196.98 billion allocated towards ongoing projects in the country, [22]. The promotion of energy conservation has resulted in increased adoption of renewable energies for instance solar, wind, biomass, trash, and hydropower among Indian citizens. The evidence suggests that clean energy sources are less environmentally damaging and frequently more cost-effective. It is projected that by the year 2047, the solar energy capacity is anticipated to exceed 750 GW, while the wind energy capacity is projected to progress to 410 GW in India, [22]. The promotion of renewable energy technology can be facilitated through a combination of persuasion policies and influence mechanisms, supported by specific methods, [61].

4 Challenges in the Renewable Energy Sector of India

Although encouraging, India's progress in renewable energy is not without its own set of challenges. Renewable energy is increasingly assuming a significant role in the diverse energy production portfolio throughout different regions of India. The broader implementation of renewable energy sources continues to encounter significant obstacles. Certain factors can be attributed to different renewable energy technologies, while others can be attributed to the current dynamics of the marketplace, regulatory frameworks, and infrastructure, [59].

4.1 Production Cost

One of the primary challenges currently impeding the widespread adoption of renewable energy is its economic viability, specifically the expenses associated with constructing and implementing infrastructure such as solar or wind farms. Renewable energies, for instance, solar and wind energy are more cost-effective to operate in resemblance to fossil fuels. The primary expenditure associated with the enactment of renewable energy technologies lies in the installation phase. The expenditures linked with installing renewable energy structures can lead lenders to perceive them as being more susceptible to risk, resulting in increased borrowing rates and greater challenges in justifying the financial feasibility of such investments. Coincidentally, in terms of fossil fuel power plants, the escalating costs of fuel can be transferred to consumers, who generally perceive the substantial fluctuations in prices as an inherent reality, [62].

4.2 Energy Transmission

To effectively harness the potential of renewable energy resources, a substantial amount of additional transmission infrastructure is necessary. Throughout the 20th century, the development of power transmission infrastructure was primarily focused on accommodating the requirements of major fossil fuel and nuclear power facilities. For instance, offshore wind farms represent a promising avenue for the extension of renewable energy sources.

4.3 Entry Barriers

The dominance of fossil fuels has resulted in substantial market power for the utilities operating these established systems, hence creating a formidable obstacle to the adoption and incorporation of renewable energies. Renewable energies, for instance, solar and wind energy, face significant challenges in competing with well-funded entities, established infrastructure, and extensive expertise and policy frameworks. Start-up enterprises encounter significant obstacles to market entry, mostly due to the presence of dominant industry incumbents. To demonstrate their worth, start-up companies must exhibit a capacity for scalability, as investors commonly want substantial levels of energy generation, a task that can present considerable difficulties. Increased government investment in clean energy, facilitated by the provision of subsidies and implementation of other relevant measures, has the potential to promote fairness and equity in the energy sector, [63].

4.4 Power Availability

A prominent issue within the realm of renewable energies is the dependence on natural resources for power generation, which are beyond human control. Solar power generation is contingent upon the presence of sunlight, operating exclusively during daylight hours and ceasing at night. Similarly, wind energy production relies on the accessibility of wind, and if wind speeds are extremely low, the turbine will remain stationary, resulting in a complete absence of power transmission to the grid.

4.5 Power Quality Concerns

The maintenance of a continuously high-power quality is crucial to guarantee the firmness and optimal effectiveness of the grid. The efficacy of the power allocation is vital in facilitating optimal system performance, characterized by enhanced dependability and reduced operational expenses. The detrimental impact of inadequate power quality on both the power grid and industrial operations is significant. The phenomenon has the potential to result in substantial financial expenses and the malfunctioning of equipment.

4.6 Location of Resources

Most renewable energy facilities that contribute their generated power to the electrical grid necessitate substantial land expanses. The utilization of renewable energy sources is often contingent upon geographical factors, a characteristic that may deter potential users. Initially, it should be noted that certain renewable energy sources may be geographically constrained and thus not readily accessible in various places. Furthermore, the proximity between the source of renewable energies and the grid has a significant role concerning both cost and efficiency. Moreover, the viability of renewable energy sources is contingent upon variables such as weather patterns, climatic conditions, and geographical positioning.

4.7 Information Gap

Although there have been notable advancements in this sector, there is a dearth of knowledge and understanding regarding the advantages and necessity of renewable energies. Financing and budgets for capital have been provided to facilitate the adoption and deployment of renewable energy technologies. There exists a discernible necessity for governmental entities to provide guidance and counsel to those seeking to apply for subsidies related to renewable energy, thereby facilitating the application process. It is imperative to cultivate community awareness of renewable energy, with particular attention to the socio-cultural practices prevalent within these areas, [64].

4.8 Political Effect

Industries with substantial financial worth often possess significant political leverage, and the fossil fuel sector is not an anomaly in this regard. The remainder energy industry in numerous nations is supported by the provision of subsidies, tax exemptions, inducements, and control gaps. Although these benefits have likely contributed to increased output, they have also redirected resources that may have otherwise been allocated toward the spread of renewable energy.

4.9 Policy and Strategies

Explicit regulations and legal procedures are necessary to attract investors and foster growth in the renewable energy market. The authorization of private sector initiatives is now experiencing delays due to an absence of well-defined policies. The nation must implement strategies aimed at enticing private investors. Regulatory agencies must develop the requisite standards and regulations on hybrid systems. The implementation of efficient regulations and tax incentives that facilitate investment can yield social benefits that extend beyond the economic rewards, [65].

4.10 Technology and Infrastructure

The challenges posed by insufficient technology and the lack of necessary infrastructure for the implementation of renewable technologies need the prioritization of research and development efforts. To establish a dependable system, it is highly recommended that a combination of renewable resources be employed in a hybrid architecture, alongside traditional sources and storage devices, [66].

4.11 Financing

The government must allocate additional financial resources to bolster research and innovation endeavors within this area. Governments must provide support for investments aimed at facilitating the expansion of renewable energies, to speed up commercializing these technologies. It is recommended that the Indian government implement a comprehensive fiscal aid program, encompassing measures such as the facilitation of credit, loan deductions, and tariff adjustments, [59].

4.12 Renewable Energy Surplus

Recently, there has been a significant expansion in the manufacturing of solar panels by governments and commercial firms worldwide. Nevertheless, despite the industry's expansion, the significant increase in panel production has resulted in an excess supply scenario. Due to the prevailing surplus of supply in the market, enterprises are adopting measures to reduce their long-term investments and, in some cases, face the possibility of closure. Millions of dollars have been lost by investors consequently. The current surplus of supply has the prospective of intensely impeding the development of solar energy technologies in the future. This has the prospective of resulting in the disruption of its long-term adoption.

4.13 Skilled labor force

The construction of more renewable energy power plants by the government necessitates the availability of a skilled labor force.

5 Renewable Energy Policies and Future Prospects in India

India's primary focus lies in the pursuit of economic progress and the amelioration of poverty. Nevertheless, the magnitude and expansion of a nation's population have a substantial impact on energy consumption patterns, [59]. India, with a population of over 1.41 billion individuals, holds the second position among the countries with the highest population. The electrical energy consumption observed from 2021 to 2022 amounted to around 1915 TWh, accompanied by a peak electricity demand of nearly 300 GW. The augmented prevalence of urbanization and the concurrent elevation of income levels have contributed to a heightened need for electrical equipment, [67]. Furthermore, India has been poised to attain universal household power access. The Republic of India faces issues in meeting the increasing demand for energy due to its reliance on imported energy resources and the lack of consistent reform in the energy segment, [22]. There is a projected rise of 156% in India's energy use from 2017 to 2040. Between the years 2017 and 2040, it is anticipated that there will be a significant rise in primary energy use obtained from fossil fuels, amounting to a projected increase of 120%, [68]. The government's twelfth quinquennial plan aimed to achieve an increase of 94 GW of electricity generation capacity over the designated time frame, with an estimated expenditure of $247 billion. According to the proposed strategy, the aim is to achieve a total installed capacity of 700 GWe by the year 2032 to accommodate a `projected 7-9% increase in GDP. This plan includes the incorporation of 63 GWe of nuclear power. India is actively pursuing nuclear investment to address the scarcity of fossil fuels and meet its electricity demands. India aims to attain a 25% contribution from nuclear power by the year 2050.

By 2040, India is projected to experience the most rapid growth in energy consumption compared to other prominent economies. This surge in demand will primarily be met by coal, with renewable energies also playing a considerable role. In 2020, renewable energy surpassed both gas and oil to become the second most prominent domestic power production source, [22]. The projected growth of renewable energy demand in India is expected to be significant, with an estimated expansion from 17 Mtoe in 2016 to 256 Mtoe in 2040. This represents a yearly expansion of 12%, [22]. It is projected that India will require an estimated investment of approximately $1.6 trillion in the domains of electricity generation, transmission, and distribution until the year 2035, [22]. The Technology Development and Innovation Policy (TDIP), which was published in 2017, aimed to facilitate the advancement of research, development, and demonstration (RD&D) activities within the renewable energy industry in India. The assessment of standards and resources, as well as the examination of processes, materials, components, products, services, and sub-systems, was conducted via RD&D activities. RD&D efforts have led to significant advancements in the market, resulting in enhanced efficiency, reduced costs, and the promotion of commercialization. These developments have facilitated scalability and bankability, aiding the inclusive expansion and success of the industry. Similarly, the incorporation of renewable energy into the overall electrical composition has resulted in self-sustainability, industrial competitiveness, and profitability, facilitated by RD&D efforts. The RD&D program assisted in the advancement and validation of technologies in many renewable energy sectors, including wind, solar, wind-solar hybrid, biofuel, biogas, hydrogen fuel cells, and geothermal energies.

As of February 2023, the entire installed capacity of renewable energies in India is at 169 GW. Among the various sources, solar power comprises 64.38 GW, hydropower includes 51.79 GW, wind power contributes 42.02 GW, and bioenergy represents 10.77 GW. Approximately 21% of the cumulative installed power capacity may be attributed to renewable energy, while the remaining 79% is derived from traditional sources. Among the Indian states, Rajasthan holds the highest position in terms of installed capacity of cumulative renewable energy, with a total of 24.46 GW. Following closely behind is Gujarat, ranking second with 21.07 GW, while Karnataka secures the third position with 20.60 GW. Tamil Nadu occupies the fourth spot with 20.35 GW, and Maharashtra rounds out the top five with 16.10 GW. The installed capacity of renewable energies in India is predominantly concentrated in these five states, accounting for around 61% of the total. The government is currently engaged in the construction of further renewable energy power facilities, necessitating the establishment of a corresponding labor force. The burgeoning investments in renewable energies can generate a greater number of employment opportunities than any other sector reliant on fossil fuels. This shift will yield substantial financial gains for both local businesses and the renewable energy sectors.

Policymakers have increasingly recognized socio-economic sustainability as a shared objective. Numerous initiatives and programs have been implemented to foster sustainability, [69]. However, global warming and climate change present significant obstacles to achieving sustainability, which can be traced to underlying social and economic factors, [70]. The primary objective of the International Federation of Global and Green Information Communication Technology (IFGICT) is to promote and attain the environmentally sustainable implementation and utilization of information and communication technology (ICT) within society. Like other developing nations, India has implemented several policies, legislation, guidelines, and other measures for the preservation and safeguarding of the environment. For the past four years, India has experienced a twofold increase in its renewable electricity capacity. India is ranked fourth regarding the total installed capacity in the wind and solar sectors, fifth in hydropower, and 13th in nuclear energy. Additionally, in 2024, the cumulative installed capacity of renewable energies places it in the third position on a global scale. The cumulative installed solar capacity has had a growth of almost eightfold throughout the past five years. The efficiency and performance of solar streetlights and solar home lighting systems have experienced a twofold enhancement. Around three million solar bulbs have been disseminated among pupils. The installed capacity of wind power has experienced a twofold rise during the past five years. India is recognized as a prominent global producer of contemporary bioenergy and exhibits substantial aspirations to expand its use throughout various sectors of the economy. Approximately five million residential biogas plants have been implemented as part of the biogas expansion project, which falls short of the predicted overall potential of 12 million such plants as determined by the MNRE. The nation has released comprehensive guidelines for conducting competitive bidding processes in the renewable energy segment. Moreover, it was found that the implementation of the lowest tariff and transparent bidding technique led to a significant reduction in the per unit price of renewable energy, [22].

The renewable energy industry in India has grown its appeal to both international and domestic investors. The World Bank has approved a funding package of $1.5 billion to support the expansion of India's low-carbon energy segment, [71]. Financial assistance amounting to 50% of the project cost was provided for technology support and experiment ventures, as well as other creative ventures on renewable energy, [22]. The burgeoning ventures in the renewable energy segment can generate a greater number of employment opportunities compared to alternative industries reliant on fossil fuels, [72]. The observation is made that the price of electricity generation through renewable technologies is advanced compared to traditional generating methods. However, it is anticipated that this cost will decrease as experience in the relevant techniques continues to grow. The collaboration between the ministry and other financial and technical organizations has played a significant role in facilitating the advancement of renewable energies and the modification of India's energy portfolio. The nation is actively involved in the promotion and consumption of renewable energies, having already initiated numerous extensive sustainable energy initiatives aimed at facilitating the substantial expansion of green energy resources, [59].

The declaration made by India, stating its objective to achieve carbon neutrality by 2070 and to fulfill 50% of its electricity need through renewable energies by 2030, is a momentous milestone in the worldwide endeavor to combat climate change. India is at the forefront of implementing a novel framework for economic development, which has the potential to circumvent the carbon-intensive strategies adopted by numerous nations in the past, [55]. This pioneering strategy could serve as a guiding template for other emerging economies. The magnitude of the transition occurring in India is remarkable. The nation in question has had substantial economic growth over the previous twenty years, ranking among the highest globally. This progress has resulted in a significant poverty reduction, positively impacting the lives of millions of individuals, [73]. Coal and oil have played pivotal roles in facilitating India's industrial expansion and modernization, enabling an increasing number of Indian citizens to avail themselves of contemporary energy services. Over the past decade, there has been an annual increase in electrical connections for over 50 million individuals. The vast dimensions of India and its substantial potential for expansion imply that its energy requirements are projected to surpass those of any other nation in the next decades. To attain a trajectory toward achieving net zero emissions by the year 2070, a significant portion of the anticipated growth in energy demand throughout this decade must be fulfilled through the utilization of low-carbon energies. Hence, it is logical that Prime Minister Narendra Modi has declared more aspiring objectives for the year 2030. These objectives encompass the installation of 500 GW of renewable energy capacity, a 45% drop in the emissions intensity of the nation's economy, and the mitigation of one billion tons of CO_2 emissions. Due to advancements in technology, consistent legislative backing, and the dynamic involvement of the private segment, the construction costs of solar power plants have become more economical compared to those of coal power plants.

The growth of renewable electricity in India is outpacing that of any other large nation, with projections indicating that new capacity additions will quadruple by 2026. India has already established a multitude of policy initiatives that, if effectively executed, may effectively tackle various difficulties by expediting the transition to cleaner and more efficient technology, [74]. The use of clean energy represents a substantial economic opportunity. India possesses a unique advantage that positions it favorably to assume a prominent role as a worldwide frontrunner in the fields of renewable batteries and green hydrogen. By 2030, the implementation of various low-carbon technologies in India has the potential to generate a market valued at approximately $80 billion. The utilization of green hydrogen is projected to have a significant influence on the attainment of net zero emissions and the reduction of carbon dioxide (CO_2) in sectors that are challenging to decarbonize. India is strategically positioning itself to emerge as a prominent global center for the production and exportation of green hydrogen, [51]. India has the potential to generate a significant demand for 5 million tons of green hydrogen, which could effectively replace the application of gray hydrogen in both the refinery and fertilizer sectors, [22]. India, being a substantial emerging economy with a population of over 1.41 billion, possesses climate adaptation and mitigation aspirations that extend beyond its national borders, impacting the global community as a whole, [59]. NITI Aayog and the IEA have established a mutual commitment to collaborate to facilitate India's sustainable growth, industrialization, and enhancement of the inhabitants' quality of life, while concurrently minimizing carbon emissions, [22].

India is ranked fourth globally in terms of its installed wind power capacity, second in biogas generation, seventh in solar PV cell output, and ninth in solar thermal systems. India's investment in renewable energy is increasing. Due to a positive legislative and policy climate, as well as a rising number of entrepreneurs and project developers, India is currently ranked as the third most appealing country for investing in renewable energy, following the USA and Germany. India, being the sole country with a dedicated ministry for renewable energy development, now possesses 13.2 GW of renewable energy (excluding large hydro), which accounts for around 8% of its total electrical capacity. Nevertheless, sources of renewable energy other than hydroelectricity are projected to account for only 5-6% of India's energy composition by 2031-32, according to the Planning Commission. India possesses immense potential for renewable energy from diverse sources, and a higher dependence on renewable energy sources presents substantial economic, social, and environmental advantages. Given the abundance of small hydro projects in mountainous regions, the implementation of small-scale hydropower for decentralized electricity production would result in the electrification of rural areas and the advancement of local communities. Solar thermal technologies possess significant potential for utilization in solar water heating systems for both industrial and home purposes, as well as for solar cooking in residential settings. This might be rendered economically feasible by the implementation of government tax incentives and refunds. Biomass plantation-based power projects can create employment opportunities by including the collection, storage, handling, and utilization of biomass materials, particularly in rural regions. Additionally, these projects can contribute to the development of rural industries and the generation of employment in rural areas. The Government of India aims to establish a sustainable urban center, commonly referred to as a 'green city', in each state across the nation, with a primary focus on utilizing renewable energy sources for electricity generation.

6 Renewable Energies for Achieving SDGs in India

6.1 Renewable Energies and No Poverty (SDG1)

There exists a symbiotic relationship between energy and the elimination of poverty. The promotion of energy development in India has the potential to generate employment opportunities, foster the emergence of novel sectors, and enhance the economic well-being of individuals with lower incomes. The application of renewable energies has the potential to enhance India's energy efficiency, resulting in energy conservation. The conservation of India's energy resources presents an opportunity to allocate additional resources towards the construction of infrastructure and the production of essential goods, thereby contributing to poverty alleviation efforts. Simultaneously, the advancement of clean energy would contribute to the amelioration of climate conditions and mitigation of environmental pollution in India, consequently diminishing the population afflicted by poverty resulting from severe or extreme weather events.

6.2 Renewable Energies and Zero Hunger (SDG2)

The provision of cost-effective, dependable, and renewable energies has the prospective to mitigate food insecurity and boost food accessibility in a densely populated country like India. The establishment of a comprehensive power grid in the agricultural sector has the potential to promote agricultural mechanization and modernization, hence improving the efficiency and productivity of food production in India. The process of decarbonizing the energy infrastructure through the promotion of renewable energies has been shown to have a positive effect on the climate environment. This, in turn, has the potential to enhance food production and mitigate losses. As an illustration, the phenomenon of climate change has the potential to result in a decrease of over 10% in the yields of maize and sorghum crops in the South Asian region, [75]. However, this undesirable outcome could be mitigated by the process of decarbonizing the energy mix. Moreover, bioenergy and hydropower exhibit significant relevance to the field of agriculture. The utilization of first-generation food-based bioenergy has the potential to result in a significant 35% escalation in worldwide food costs under a 2°C scenario, [76]. However, the advancement of second-generation bioenergy, which is derived from non-food sources, as well as third-generation bioenergy derived from algae, presents a promising opportunity to circumvent any conflicts with food production, [77].

6.3 Renewable Energies for Good Health and Well-Being (SDG3)

The development of India's renewable energies as a substitute for fossil fuels yields multiple advantages for the environment, climate, and human health. The combustion of traditional fossil fuels results in the emission of significant quantities of atmospheric pollutants, including CO_2, nitrogen dioxide, sulfur dioxide, and particulate matter. These emissions have been associated with adverse health effects, such as cardiovascular diseases, respiratory ailments, lung cancer, and hypertension, contributing to a global annual mortality rate exceeding five million individuals, [78]. The over utilization of fossil fuels leading to the greenhouse effect has the potential to worsen psychological disorders, with post-traumatic stress disorder, depression, heightened anxiety, mental illness, and impulses towards suicide. On the contrary, the mitigation of air pollution can decrease the mortality rate linked with the greenhouse effect by facilitating the widespread usage of renewable energies. Furthermore, the implementation of renewable energies would enhance India's energy systems and infrastructure within hospitals, medical centers, and other healthcare institutions.

6.4 Renewable Energies and Quality Education (SDG4)

There exists a discernible correlation between the advancement of renewable energy sources and the enhancement of educational standards. The presence of a contemporary energy system establishes the necessary infrastructure for the optimal development and advancement of educational endeavors. An uninterrupted and dependable electrical infrastructure is vital for educational institutions such as colleges and schools to effectively conduct their educational and instructional endeavors. The provision of inexpensive renewable energies on a universal scale holds significant importance in enhancing educational circumstances and fostering learning possibilities in rural and underdeveloped regions in India. Consequently, a quality education not only facilitates public comprehension of the implications of sustainable development and facilitates the implementation of renewable energy legislation, but also augments the proficiency of personnel within the energy industry, [79]. Education has the prospective to improve the utilization of renewable energy and foster environmental consciousness across many strata of society, [80] in India.

6.5 Renewable Energies and Gender Equality (SDG5)

The expansion of renewable energy technology has the potential to expedite the modernization of energy and industrial infrastructures, while also enhancing the efficient deployment of industrial resources in India. Consequently, there is an anticipated large increase in the availability of employment opportunities that are acceptable for women, [81]. The provision of affordable energy costs has the potential to reduce household expenses and potentially facilitate more educational possibilities for women and girls in India. Consequently, women are anticipated to have enhanced career prospects, wage levels, work environments, and social statuses, enabling them to engage in more equitable competition with men in middle and senior-level positions. Moreover, it is a common practice among numerous households in India for women to assume the role of culinary preparation. The utilization of clean cooking fuels has the potential to mitigate the adverse effects on individuals' health, particularly the women living in the rural part of India.

6.6 Renewable Energies for Clean Water and Sanitation (SDG6)

Typically, fossil energy sources are harnessed amid the process of combustion, necessitating the use of water for equipment cooling purposes. The implementation of clean energy technologies and the enhancement of energy efficiency have the potential to mitigate the demand for cooling, hence leading to water conservation. As an illustration, traditional thermal power plants typically require a water consumption ranging from 550 to 10,000 liters per megawatt-hour (L/MWh), but solar generating facilities have a significantly lower water consumption of approximately 125 L/MWh, [82]. The utilization of waste heat derived from India's nuclear power reactors to desalinate saltwater has the potential to augment the availability of freshwater supplies, [83]. Furthermore, the development of contemporary energy systems can enhance the sustainability of water transmission, pumping, and purification infrastructure, thereby contributing to the goal of providing universal access to potable water, [84].

6.7 Renewable Energies as Affordable and Clean Energy (SDG7)

The cost of renewable energies is falling, while simultaneously increasing their reliability and efficiency in India. The implementation of energy-efficient practices and the promotion of renewable energies portray a significant position in mitigating climate change and reducing the risks associated with natural disasters in India. The achievement of SDG 7 by 2030 necessitates the imperative of allocating resources towards investment in renewable energies, enhancing energy efficiency, and guaranteeing universal access to energy.

6.8 Renewable Energies for Decent Work and Economic Growth (SDG8)

The development of renewable energies facilitates job creation and employment prospects, serving as a fundamental driver for economic and social progress in India. During the process of transitioning to low-carbon energy, it is anticipated that there will be significant transformations in energy, industrial, and economic systems, as well as employment patterns. These changes are projected to present novel prospects for India to reconfigure societal production and enhance its global competitiveness. The systematic advancement of clean energy can facilitate the gradual disentanglement of economic growth from reliance on fossil fuels and the resulting environmental deterioration. This, in turn, can enhance the overall quality and sustainability of the Indian economy while also generating a greater number of excellent employment opportunities. Based on the findings of the International Labor Organization, it is projected that India's transition towards a green economy will potentially yield the generation of over 3 million employment opportunities in the renewable energy segment, by the year 2030, [73].

6.9 Renewable Energies for Industry Innovation and Infrastructure (SDG9)

The expansion of renewable energies stimulates innovation within industries and facilitates the renewal of infrastructure. A rapid transition from coal sectors and more ventures in new power supplies are necessary to achieve a considerable rise in the proportion of renewable energies, [85]. A robust and durable infrastructure is a fundamental requirement for the advancement of energy development. The utilization of contemporary digital, information-based, and intelligent infrastructure, with the integration of progressive industrial technologies, for instance, big data and blockchain, has the potential to enhance India's energy efficiency and foster creativity. Moreover, these advancements can contribute to the widespread availability of dependable renewable energy services in India.

6.10 Renewable Energies for Reducing Inequalities (SDG10)

The growth of the renewable energy sector has a crucial role in promoting energy affordability and universality, contributing to the decline of energy poverty and the mitigation of local, national, and global disparities, [86]. Enhancing energy efficiency via the expansion of the renewable energy segment has the potential to mitigate material inequality by allocating a greater share of energy resources towards enhancing material conditions. The expansion of renewable energy systems is anticipated to lead to a gradual decentralization of energy supply, enabling the general population to attain more equitable and convenient access to energy services, including power and heat. Electricity has a crucial role in facilitating the distribution of knowledge and information, hence contributing to the reduction of educational disparities. The growth of renewable energy also serves as a significant influence in augmenting the income of individuals in poverty and mitigating income disparity, [87].

6.11 Renewable Energies for Sustainable Cities and Communities (SDG11)

Urban areas are characterized by high population density, significant infrastructure investments, and a heightened susceptibility to calamities. The exploitation of fossil fuels adds to varying degrees of urban pollution, notably in the form of air pollution. The utilization of renewable energies for energy modernization and decarbonization has the potential to foster urban upgrading and inclusivity, mitigate urban climate risks, enhance urban air quality, and safeguard urban ecosystems in India. A dependable and effective electricity provision is a fundamental requirement for delivering superior living amenities to urban inhabitants, promoting eco-friendly transit options like subways and electric vehicles, and constructing secure and environmentally sustainable residential, commercial, and business areas.

6.12 Renewable Energies for Responsible Consumption and Production (SDG12)

The extensive utilization of fossil fuels in consumption and industrial practices contributes to environmental negligence, while the historically inadequate energy efficiency results in the squandering of energy resources, [88]. To attain sustainable and responsible development in India, it is necessary to implement significant alterations to previous production and consumption patterns. The advancement of renewable energies in India could play a crucial role in mitigating waste and pollution, serving as a significant means to foster a low-carbon, environmentally sustainable, and socially responsible approach to consumption and production within the broader socioeconomic framework.

6.13 Renewable Energies for Climate Action (SDG13)

There exists a strong correlation between energy and climate change. The primary anthropogenic factor causing global warming and climate change is the emission of CO_2 and other GHGs resulting from the utilization of fossil fuels, [89]. The substitution of fossil fuels with renewable energies in the Indian energy portfolio is a fundamental strategy for attaining carbon neutrality and mitigating the effects of climate change and its associated consequences in India. According to the Intergovernmental Panel on Climate Change (IPCC), it is recommended that the proportion of low-carbon energy in the worldwide primary energy supply surpasses 70% by 2050, to effectively mitigate global warming and uphold the temperature upsurge below 1.5 degrees C, [90]. To attain carbon neutrality by the year 2070, it may be necessary for India to ensure that renewable energy constitutes around 50% of its energy mix by the year 2030.

6.14 Renewable Energies and Life below Water (SDG14)

The utilization of ocean energy has seen a progressive increase, mostly encompassing offshore solar energy, offshore wind energy, wave energy, tidal energy, and marine bioenergy. A stable marine ecology fosters a sustainable yield environment for marine energy generation, [91]. The expeditious popularization of clean energy in marine operations is anticipated to effectively preserve marine ecology. One potential consequence of climate change is the potential reduction in marine fishing capacity, a situation that could be mitigated through the promotion and widespread use of sustainable energy sources.

6.15 Renewable Energies and Life on Land (SDG15)

The implementation of renewable energy sources in impoverished and underdeveloped regions in India can effectively mitigate the reliance on fuelwood and thus minimize the detrimental impact on forests, meadows, and land. This approach contributes to the preservation of terrestrial and vegetative organisms, while also ensuring the sustenance of local ecosystems and biodiversity, [49]. The conservation of biodiversity has the potential to offer nature-based solutions, such as carbon sinks, as well as technical ones, such as bioenergy with carbon capture and storage, to attain carbon neutrality in India.

6.16 Renewable Energies for Peace Justice and Strong Institutions (SDG16)

The construction of numerous government agencies and international organizations, such as the International Energy Agency (IEA), has been motivated by the advancement of energy development. These entities play a key role in fostering a harmonious and regulated framework for energy-related endeavors. The presence of peaceful societies, equitable access to justice, and responsible institutions serve as crucial protective measures for energy growth across India. The participation of impartial, unbiased, and reputable organizations in India can function as a means of facilitating communication to effectively address conflicts and arrive at energy-related decisions that are more suited to local contexts. In certain geographical areas in India characterized by unfavorable market conditions and ineffective market regulations, the impartial intervention of government institutions could play a key role in fostering the growth of energy development.

6.17 Renewable Energies and Partnerships for the Goals (SDG17)

Energy has facilitated the establishment of several international collaborations in various domains, including resource allocation, technological advancements, financial investments, and knowledge exchange, across nations. Renewable energy technologies and investments are a significant component of the "Belt and Road" Initiative, [92]. Partnerships hold significant potential in facilitating global energy interconnection, fostering collaboration, and sharing resources to promote the advancement and sustainability of energy systems at a worldwide level. Throughout COVID-19 retrieval, the establishment of active international collaborations can play a crucial role in fostering political consensus on energy matters, fostering a greater sense of enthusiasm toward the advancement of renewable energy sources, and mitigating obstacles and expenses associated with energy development.

7 Conclusions and Policy Recommendations

Renewable energies have appeared as a prominent option for addressing the energy crisis and environmental concerns, as it replaces fossil fuels. The objective of this study is to conduct a thorough analysis of the present situation and future potential of renewable energies in India. This involves reviewing government policies, identifying obstacles and incentives, and assessing the influence of renewable energies on the country's sustainable growth. The Indian renewable energy segment is ranked as the third most desirable market for renewable energies internationally. India’s installed capacity of renewable energies in the year 2023 is recorded at 169 GW, with 64.38 GW of solar power, hydropower 51.79 GW, wind power 42.02 GW, and biofuel representing 10.77 GW. Among the Indian states, Rajasthan holds the highest position in terms of installed capacity of cumulative renewable energy, with a total of 24.46 GW, followed by Gujarat (21.07 GW), Karnataka (20.60 GW), Tamil Nadu (20.35 GW), and Maharashtra (16.10 GW). These five states collectively account for approximately 61% of the total installed capacity of renewable energies in India.

The present study’s findings indicate that India possesses significant potential for the expansion of the renewable energy industry to attain environmental sustainability and enhance energy efficiency. The Indian government is actively involved in the development of large-scale renewable energy projects and implementing effective energy policies, to install 500 GW of renewable energy capacity by 2030, along with the production of 5 million tonnes of green hydrogen within the same timeframe. By 2030, 50% of India's total electricity generation will be derived from non-fossil fuel sources. The present study provides evidence of the potential of renewable energy sector expansion in India to contribute towards the accomplishment of all 17 SDGs outlined by the United Nations. The findings of this research hold the potential to support the formulation and execution of suitable policies targeted at the advancement of India's renewable energy industry. Additionally, these policies can assist in emission reduction and the attainment of climate objectives by stimulating the adoption of renewable energies, ultimately working towards the achievement of the SDGs.

The article outlines the following recommendations intended to enhance the progress of renewable energy development in India.

- The enactment of governmental policies targeted to promote renewable energies and sustainable development is a potential course of action.
- The potential for enhancing sustainable development in India could be heightened through the adoption and implementation of effective regulations aimed at managing industrial sector practices inside the country.
- The Indian government needs to develop and implement comprehensive plans that apply to diverse social classes and varied industry sectors.
- Energy consumption in India is predominantly dependent on conventional power sources characterized by substantial carbon emissions. Thus, the potential long-term impacts of escalated utilization of renewable energy sources on carbon emissions and industrialization urge investigation.
- The transition from fossil fuels to renewable energies has the prospective to play a noteworthy role in the Indian economy. To reduce the cost of this transition, it is imperative to integrate private sector investment into renewable energy initiatives.
- India needs to adopt strategies aimed at reducing the price of renewable energies, while concurrently curbing the utilization of fossil fuels within industrial, commercial, and residential segments.
- The government would also promote the adoption of energy-efficient residential equipment and cost-effective renewable energies within the households.
- The formulation and maintenance of suitable government policies may catalyze promoting investment in the advancement of renewable energy technologies, ultimately leading to a notable upsurge in the utilization of renewable resources.
- Renewable energy projects might be funded by the government through the establishment of public-private partnerships.
- India should increase financing to overcome financial constraints, enhance technology capabilities, improving grid infrastructure while strengthening policy implementation to accelerate the transition to renewable energy sources.
- It is imperative to secure assistance from the international community to facilitate the transition of India's development towards a trajectory characterized by reduced carbon emissions.
- The attainment of net zero entails more than only mitigating GHG emissions. The energy transition in India should prioritize the welfare of its population, and the implementation of well-crafted regulations can mitigate the possible conflicts between affordability, security, and sustainability.
- India may strengthen the technical cooperation agreements with technologically advanced nations, all the while actively engaging in proactive research on renewable energy technology.
- The involvement of local authorities and non-governmental organizations (NGOs) may play a vital role in enhancing environmental consciousness among individuals of diverse age groups through the dissemination of knowledge on renewable energy technologies and energy efficiency. The attainment of this objective can be facilitated through the implementation of training and instructional initiatives inside educational institutions, such as schools and universities.
- Various fiscal strategies can be employed by authorities to incentivize individuals to transition towards greener energy sources. These strategies encompass the provision of tax breaks, monetary support, and the allocation of government contracts.
- The Indian government may utilize the media to promote its green living philosophy, which may include low-carbon lifestyles and alterations in consumer behavior.

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