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Tracking India's rise in renewable energy: Capacity, composition and comparisons

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Abstract

India has emerged as a major player in the global renewable energy landscape, demonstrating substantial growth in installed renewable capacity over the past two decades. This study employs descriptive statistical analysis of secondary data obtained from the International Renewable Energy Agency (IRENA) to examine India's renewable energy development in terms of capacity, composition, and global comparison. The analysis reveals that India's renewable energy capacity grew from 25 GW to 176 GW between 2003 and 2023, representing approximately 4.5% of the global total and ranking India fourth in the world, behind China, the United States, and Brazil. During the same period, non-renewable capacity expanded from 93 GW to 329 GW. Despite this, the share of renewables in India's total electricity capacity increased steadily from 21% in 2015 to 35% in 2023. However, India lags significantly in per capita installed capacity, standing at only 0.12 kW for renewables and 0.35 kW for total electricity, far below Brazil, China, the U.S., and Canada. The study also highlights India's technological composition: solar energy leads the renewable mix, followed by nearly equal shares of hydro and wind, with bioenergy contributing only 6.11%. Almost all renewable sources are grid-connected due to high energy storage costs. Unlike global trends, India has no offshore wind or mixed hydro installations and heavily relies on onshore wind and solid biofuels. While India demonstrates a balanced technological approach, significant disparities remain in per capita metrics and technological diversity. These findings underscore the need for targeted policy to improve equity and expand innovation in renewable deployment.

Keywords: Renewable energy; Installed capacity; Energy composition; Solar energy; Wind energy

1. Introduction

The 21st century has marked a transformative era in the global energy sector. As concerns over environmental degradation, climate change, and the depletion of fossil fuels intensify, renewable energy (RE) has emerged as a cornerstone of sustainable development (Debnath et al, 2023). Across the globe, nations are increasingly investing in alternative energy sources such as solar, wind, hydro, and bioenergy to meet growing energy demands while reducing greenhouse gas emissions (Siraj et al., 2024). In this global transition, India, a country with the world's largest population and one of the fastest-growing economies, has increasingly drawn attention for its substantial efforts in scaling up renewable energy.

Over the past two decades, India has made remarkable progress in renewable energy development, both in terms of policy frameworks and installed capacity. Driven by the twin imperatives of energy security and environmental sustainability, India's government has undertaken numerous strategic initiatives, including the National Action Plan on Climate Change (NAPCC), the National Solar Mission, and the more recent Renewable Energy Roadmap targeting 500 GW of non-fossil-based capacity by 2030 (Vishwanathan et al., 2023). These policy initiatives are further supported by

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international commitments such as the Paris Agreement, where India has pledged to reduce the emissions intensity of its GDP by 33–35% by 2030 from 2005 levels.

From an installed capacity of just 25 GW in renewable energy in the early 2000s, India has expanded to a capacity of 176 GW by the end of 2023, placing it 4th globally after China, the United States, and Brazil (Saeed and Siraj, 2024). This growth is not only numerically significant but also reflects a broad-based expansion across multiple renewable technologies. Solar energy has emerged as the leading contributor, followed by substantial shares of wind, hydro, and bioenergy. The share of renewables in India's total installed electricity capacity has grown steadily, from 21% in 2015 to approximately 35% in 2023, indicating a deliberate and strategic shift towards cleaner energy sources.

However, this rapid growth must be analyzed within a broader context. While India's absolute figures are impressive, they are accompanied by major challenges. One of the most critical issues is the low per capita installed capacity, which reflects disparities in energy access and infrastructure development (Siraj et al., 2022). India's total installed capacity across all energy sources stood at 505 GW in 2023, making it the third-largest in the world after China and the United States. Yet, when adjusted for population size, India's per capita renewable energy capacity is only 0.12 kW per person, a figure that pales in comparison to Canada's 2.8 kW, the United States' 1.85 kW, and even Brazil's 0.9 kW. The same trend is observed for total per capita electricity capacity, where India's 0.35 kW per person is significantly lower than Brazil (1.05 kW), China (2.06 kW), the United States (3.67 kW), and Canada (4.03 kW). These figures highlight the energy equity gap that continues to challenge India's energy transition narrative.

Another critical aspect of India's renewable energy profile is the composition of technologies within its total capacity. Solar energy has witnessed the most aggressive growth due to declining technology costs, policy incentives, and large-scale project development, particularly in states like Rajasthan, Gujarat, and Andhra Pradesh (Payel et al., 2023). Solar energy now constitutes the largest share of India's renewable portfolio. Wind energy, largely concentrated in Tamil Nadu, Gujarat, and Maharashtra, accounts for roughly one-fourth of the renewable mix. Hydro and bioenergy contribute smaller shares, with bioenergy forming about 6.11% of India's renewable energy capacity, primarily sourced from solid biofuels (70%).

In terms of integration, India's renewable capacity is heavily skewed toward on-grid installations. Nearly 100% of wind and hydro, 97% of solar, and 91% of bioenergy capacities are grid-connected. This reflects both infrastructural dependency and the high cost of energy storage systems such as batteries, which remain a barrier to widespread off-grid and decentralized renewable deployment. While this model supports centralized control and efficient distribution, it may limit renewable energy access in remote or underserved areas.

Comparisons with global trends further contextualize India's position. Worldwide, concentrated solar power (CSP)—a form of solar thermal energy—accounts for about 0.5% of total solar capacity, totaling 6.9 GW. India aligns closely with this global share, having installed 342.5 MW of CSP capacity. In hydroelectric energy, the global portfolio includes mixed hydro plants, which contribute 4.6% of global hydro capacity (58.35 GW). India, however, has no mixed hydro plants, with 100% of its hydro classified as renewable. Similarly, the global expansion of offshore wind energy has reached 72.7 GW, representing 7.14% of total global wind capacity, whereas India remains entirely reliant on onshore wind, with no operational offshore wind farms as of 2023.

Despite these structural and technological limitations, India maintains a balanced growth pattern across all major renewable technologies. It ranks 5th globally in solar capacity, 4th in wind, 6th in hydro, and 4th in bioenergy, reflecting a relatively even distribution of investment and development across the renewable spectrum. This diversified approach is crucial for enhancing energy security, reducing overreliance on any single technology, and ensuring resilience in the face of climate-induced variability.

Nevertheless, the path forward is not without its hurdles. Major challenges include land acquisition for large-scale renewable projects, intermittency of power supply, underdeveloped transmission infrastructure, storage limitations, and regulatory hurdles (Siraj et al., 2022). The socio-political landscape, including public resistance and displacement concerns, also complicates large-scale renewable energy deployment. Furthermore, the financial viability of projects often hinges on subsidies, incentives, and long-term purchase agreements, making the sector vulnerable to policy shifts.

Given this complex backdrop, this study aims to analyze India's renewable energy journey through a multi-dimensional lens. Specifically, it seeks to (1) examine the trends and growth in installed renewable energy capacity, (2) analyze the composition of renewable energy technologies, and (3) compare India's performance with other leading nations in order to identify gaps and opportunities. By integrating domestic data with global benchmarks, this research provides a holistic understanding of India’s renewable energy landscape—one that balances optimism with realism, growth with equity, and ambition with practicality.

2. Literature Review

India has emerged as a significant player in the global RE sector, ranking fourth worldwide in total installed RE capacity as of 2023 (International Energy Agency [IEA], 2023). This growth is attributed to robust policy frameworks, technological advancements, and increasing energy demand. The country's RE portfolio encompasses solar, wind, hydro, and bioenergy sources, with solar energy witnessing the most rapid expansion due to declining costs and supportive policies (Kumar and Majid, 2020).

Solar energy has become the dominant source in India's RE mix, accounting for a significant portion of new installations. States like Rajasthan have emerged as leaders in solar capacity, contributing substantially to the nation's solar energy output (Mahida, 2023). Wind energy continues to play a crucial role, with steady growth observed in states such as Tamil Nadu and Gujarat (Ghatak et al., 2021). Hydropower and bioenergy also contribute to the RE landscape, though their growth has been comparatively modest (Ghatak et al., 2021).

India's commitment to expanding its RE capacity is evident through various policy measures and initiatives. The National Solar Mission (NSM), launched in 2010, aimed to promote solar energy development and set ambitious targets for capacity addition (Ministry of New and Renewable Energy [MNRE], 2010). Subsequent policies have focused on creating a conducive environment for investment, streamlining regulatory processes, and providing financial incentives to attract both domestic and foreign investors (Kumar and Majid, 2020).

The expansion of the RE sector has significant economic implications, including job creation and investment opportunities. The sector is anticipated to generate a substantial number of domestic jobs in the coming years, contributing to economic development and energy security (Kumar and Majid, 2020). However, challenges such as financing, land acquisition, and infrastructure development remain critical to sustaining this growth (Kumar and Majid, 2020).

One of the primary challenges in scaling up RE is the integration of variable energy sources into the existing grid. The intermittent nature of solar and wind energy necessitates advancements in energy storage technologies to ensure a stable and reliable power supply (Mohan et al., 2021). Currently, the high cost of battery storage systems poses a barrier to widespread adoption, highlighting the need for continued research and development in this area (Mohan et al., 2021).

The rapid development of RE infrastructure, particularly solar PV installations, has raised concerns regarding land use and environmental impacts. Studies indicate that a significant portion of solar development in India has occurred on land with ecological or agricultural value, underscoring the importance of strategic planning to minimize adverse effects (Ortiz et al., 2022). Hossain et al. (2022) supports the renewable sector by offering a cost-effective approach to microbial fuel cell (MFC) development, enhancing energy storage solutions through optimized electrode materials and predictive modeling for sustainable electricity generation.

Despite the extensive literature on India's RE sector, several gaps persist: Limited studies focus on per capita RE capacity, which is crucial for understanding energy equity and access. There is a need for comprehensive analysis of the technological mix within India's RE portfolio to inform balanced development strategies. Few studies offer comparative insights between India and other leading RE nations, which could provide valuable lessons and benchmarks.

This paper aims to address these gaps by: Providing a detailed analysis of India's RE capacity growth, with a focus on per capita metrics; Examining the technological composition of the RE sector to identify areas of strength and opportunities for diversification; Conducting comparative assessments with other top RE countries to contextualize India's progress and identify best practices.

3. Methodology

3.1. Data Collection

This study is based on secondary data collected from the International Renewable Energy Agency (IRENA) database and annual reports. The dataset includes information on installed electricity capacities (total and renewable), technological composition (solar, wind, hydro, and bioenergy), on-grid and off-grid capacities, and international comparisons spanning the years 2000 to 2023.

Additional comparative data on other countries' energy capacities (e.g., China, the United States, Brazil, and Canada) have also been sourced from IRENA to benchmark India's performance within a global context.

3.2. Data Preparation

The collected data were curated and formatted in Microsoft Excel and Python (Pandas and NumPy) for consistency. The following preparation steps were undertaken:

- Data cleaning: Removing missing values, unit standardization (e.g., all capacities converted to GW or kW per capita).
- Segregation by energy type: Solar, wind, hydro, bioenergy.
- Classification: On-grid vs. off-grid, mixed vs. pure renewable sources.
- Conversion to per capita metrics using population data from World Bank datasets.

3.3. Descriptive Statistical Analysis

This study uses descriptive statistics to explore trends, proportions, and comparisons. The main statistical techniques used include:

$$\text{Absolute Growth} = C_{end} - C_{start} \quad \ldots\ldots(1)$$

where C_{end} and C_{start} denote the ending and starting values of installed capacity over the period.

$$\text{Percentage Growth (\%)} = \frac{(Cend - Cstart)}{Cstart} \times 100 \quad \ldots\ldots(2)$$

$$\text{Renewable Share (\%)} = \frac{C\ renewable}{C\ total} \times 100 \quad \ldots\ldots(3)$$

$$\text{Per Capita Capacity (kW)} = \frac{C}{P} \quad \ldots\ldots(4)$$

where C is the installed capacity (in kW) and P is the population.

$$\text{Technology Composition (\%)} = \frac{C\ tech}{C\ renewable} \times 100 \quad \ldots\ldots(5)$$

where C_{tech} refers to capacity from a specific technology like solar or wind.

3.4. Comparative Analysis

To understand India's position globally, the above metrics are computed for several countries with high renewable energy capacities. These include: total installed capacity, renewable share in total, per capita installed capacity, technology diversity and balance. These indicators allow assessment of India's energy equity, transition pace, and technological diversification.

4. Results and Discussion

Over the past two decades, India's total installed renewable energy capacity has shown a significant upward trend, increasing from 25 GW to 176 GW. During the same period, non-renewable energy capacity also expanded considerably, from 93 GW to 329 GW. Despite the faster absolute growth in non-renewable energy, the share of renewable energy in the country's total electricity mix has grown steadily. Notably, between 2015 and 2023, the share of renewables in total installed capacity increased from 21% to 35%, indicating a robust transition toward cleaner energy sources in recent years (see Figure 1).

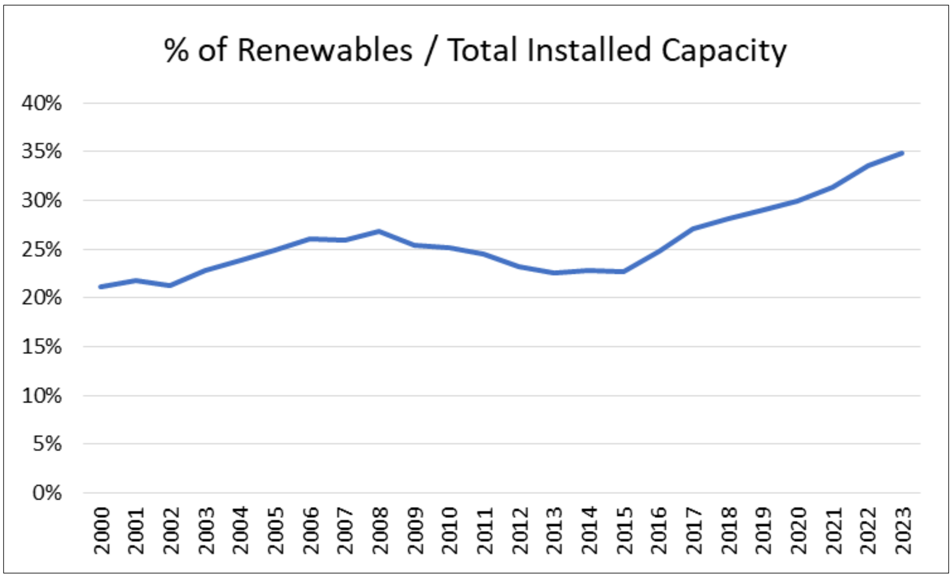

Figure 1 Increasing of renewables percentages over the years

The steady increase in India's renewable energy share—from 21% in 2015 to 35% in 2023—despite substantial growth in non-renewable capacity, indicates a clear shift toward cleaner energy sources. This trend is driven by supportive government policies, such as the National Solar Mission, declining costs of solar and wind technologies, and increased foreign investment in the renewable sector. Although non-renewable capacity grew faster in absolute terms due to rising energy demand, renewables have expanded at a higher rate proportionally, reflecting India's commitment to a low-carbon transition. However, the continued reliance on fossil fuels highlights the challenges of balancing rapid development with sustainability goals (Majumder et al., 2023).

As of 2023, India ranks 4th globally in total installed renewable energy capacity with 176 GW, following China, the United States, and Brazil (see Table 1). This capacity is close to Brazil's but significantly behind China's 1454 GW. India's renewable energy accounts for approximately 4.5% of global renewable capacity. In terms of total installed electricity capacity, including both renewable and non-renewable sources, India holds the 3rd position globally with 505 GW, which constitutes about 5% of the world's total capacity.

Table 1 Topmost 20 countries of the world according to the renewable installed capacity

Countries	**Renewable installed capacity (in MW)**
China	1453701
United States of America	387549
Brazil	194085
India	175929
Germany	166939
Japan	127328
Canada	108764
Spain	80136
France	69301
Italy	65157
Türkiye	58462
Russian Federation	56708
United Kingdom of Great Britain and Northern Ireland	55561

Australia	54328
Viet Nam	46012
Sweden	40646
Norway	40161
Netherlands	35627
Republic of Korea	34450
Mexico	33517

India's high global ranking in both renewable and total installed capacity highlights its expanding energy infrastructure and commitment to energy diversification. While the country is approaching Brazil in renewable capacity, the vast gap with China emphasizes the disparity in scale and investment. The fact that India ranks even higher in total capacity (3rd globally) suggests substantial development in both clean and conventional energy sectors to meet growing demand. However, its relatively small share in global capacity (4.5% renewable, 5% total) despite its population size points to significant potential for further expansion, especially in clean energy, to match its developmental and environmental goals.

Among the top 10 countries with the highest renewable energy capacity, India has the lowest per capita installed electricity capacity. In 2023, India's per capita renewable energy capacity stood at 0.12 kW, significantly lower than Canada (2.8 kW) and even Brazil (0.9 kW) (see Table 2). The trend is similar for total installed electricity capacity per capita, with India at 0.35 kW, far behind Brazil (1.05 kW), China (2.06 kW), the United States (3.67 kW), and Canada (4.03 kW).

Table 2 Per capita renewable energy capacity of topmost 10 countries

Countries	**Population**	**Renewable (KW)/ capita**
China	1412175000	1.029405881
United States of America (the)	333287557	1.16280546
Brazil	215313498	0.901404992
India	1417173173	0.124140786
Germany	83797985	1.992160074
Japan	125124989	1.017602487
Canada	38929902	2.793834544
Spain	47778340	1.677248665
France	67971311	1.019567594
Italy	58940425	1.105473332

Despite India's high global ranking in total renewable and overall energy capacity, the per capita figures reveal a stark contrast, highlighting the burden of its large population on energy distribution. Low per capita availability suggests that a significant portion of India's population still lacks adequate access to electricity, or that energy infrastructure is unevenly distributed. This underscores the dual challenge India faces: scaling up generation capacity while also ensuring equitable access. The data also emphasize the need for not only increasing total capacity but improving energy efficiency and expanding grid connectivity to address disparities in consumption and availability at the individual level.

In 2023, only 6.11% of India's total renewable electricity capacity originated from bioenergy, despite its large population and abundant biomass resources (see Figure 2). Solar energy holds the largest share, followed by approximately one-fourth each from hydro and wind power. In terms of connectivity, 100% of wind, nearly 100% of hydro, 97% of solar, and 91% of bioenergy capacities are on-grid, reflecting a strong emphasis on centralized electricity distribution.

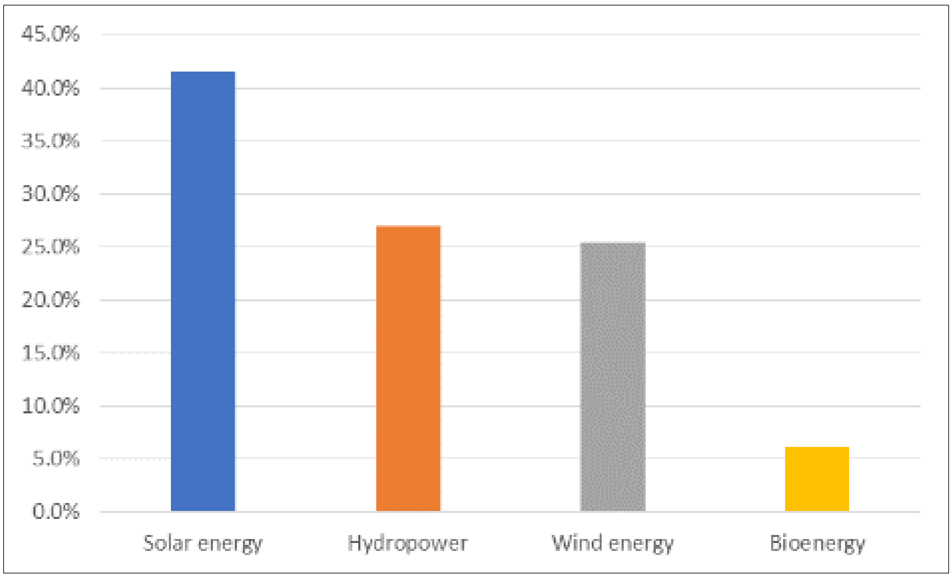

Figure 2 India's renewable energy installed capacity source-wise segregation

The relatively low contribution of bioenergy in India's renewable energy mix highlights an underutilization of potential biomass resources, which could otherwise play a significant role in rural energy access. The dominance of solar energy reflects India's strategic focus on scalable and rapidly deployable technologies supported by favorable policies and declining costs. The high percentage of on-grid capacity across all renewable sources also points to India's limited progress in off-grid renewable systems, largely due to the high cost and limited deployment of energy storage technologies, such as batteries. This trend underscores the country's prioritization of utility-scale projects over decentralized solutions, which may restrict renewable energy access in remote and underserved regions.

Globally, renewable energy sources are technologically diverse, yet India's deployment reflects a narrower focus. For example, Concentrated Solar Power (CSP) constitutes 0.5% of global solar capacity (6.9 GW), and India maintains a similar share with 342.5 MW of CSP capacity. In hydropower, 4.6% of the global capacity (58.35 GW) comes from mixed hydroplants, whereas India's hydropower is entirely renewable, with no mixed-use hydroplants. Regarding bioenergy, India relies heavily on solid biofuels, which make up about 70% of its bioenergy use. Additionally, while the world has 72.7 GW of offshore wind energy (about 7.14% of global wind capacity), India is solely dependent on onshore wind.

These figures highlight India's limited technological diversification in renewable energy deployment compared to global trends. The negligible presence of CSP, absence of mixed hydroplants, and exclusive dependence on onshore wind suggest a conservative and cost-driven technology strategy. This approach may stem from India's prioritization of low-cost, scalable solutions, such as photovoltaic solar and onshore wind, to rapidly meet growing energy demands. However, this narrow focus could limit grid flexibility, geographical optimization, and resilience in the long term. Expanding into offshore wind, hybrid hydroplants, and advanced bioenergy could provide India with a more balanced and adaptable renewable energy portfolio.

As of 2023, India ranks 4th globally in total renewable energy capacity, reflecting a diversified investment across multiple technologies. Specifically, India holds the 5th position in solar energy, 4th in wind energy, 6th in hydropower, and 4th in bioenergy capacity. These rankings indicate that India is pursuing a balanced growth strategy in renewable energy development across various sources.

India's positioning across different renewable technologies demonstrates a strategic effort to diversify its clean energy portfolio rather than over-relying on a single source. This balanced growth approach strengthens energy security, reduces dependence on fossil fuels, and enhances resilience to supply fluctuations or regional resource constraints. Although the country still faces challenges in per capita availability and energy storage, the simultaneous development of solar, wind, hydro, and bioenergy reflect policy support for a broad-based renewable transition. Such diversity is crucial for long-term sustainability and aligns with global goals for a just and inclusive energy transformation.

4.1. Implications for Developing Nations for Sustainable Energy Transition

India's remarkable progress in RE development, as outlined in the analysis, offers valuable lessons for developing nations, particularly its neighbors like Bangladesh and Pakistan, which share similar socio-economic and infrastructural challenges. The expansion of India's renewable energy capacity from 25 GW in 2003 to 176 GW in 2023, alongside its diversified technological mix and policy-driven approach, provides a replicable model for achieving Sustainable Development Goal 7 (SDG7), which emphasizes affordable, reliable, sustainable, and modern energy for all. Below, we explore key implications for developing nations, focusing on policy frameworks, technological diversification, energy equity, and regional collaboration, with specific reference to Bangladesh, Pakistan, and SDG7.

India's success in scaling renewable energy is deeply rooted in its robust policy frameworks, such as the National Solar Mission and the Renewable Energy Roadmap targeting 500 GW by 2030. These policies have attracted investment, streamlined regulations, and incentivized private-sector participation. For Bangladesh, which has made strides in solar home systems and aims to achieve 10% renewable energy by 2025 (Debnath et al., 2023), adopting similar long-term, ambitious targets supported by clear incentives could accelerate RE deployment. Pakistan, with its Alternate Energy Development Plan targeting 30% renewable energy by 2030, can learn from India's approach to balancing subsidies with market-driven mechanisms to ensure financial viability (Siraj et al., 2024). Aligning national policies with SDG7's emphasis on sustainable energy requires developing nations to establish clear, enforceable targets, coupled with financial mechanisms like tax breaks or low-interest loans to stimulate private investment.

India's balanced growth across solar, wind, hydro, and bioenergy (with solar leading, followed by wind and hydro) underscores the importance of technological diversification to enhance energy security and resilience. However, India's limited adoption of offshore wind and mixed hydro plants, compared to global trends, highlights a gap that Bangladesh and Pakistan can address early in their energy transitions. Bangladesh, with its coastal geography, has significant potential for offshore wind, which could complement its solar initiatives (Debnath et al., 2023). Pakistan, endowed with abundant wind corridors in Sindh and Balochistan, could prioritize both onshore and offshore wind to diversify from its heavy reliance on hydropower (Siraj et al., 2022). Diversifying energy sources aligns with SDG7's goal of sustainable energy by reducing dependence on single technologies and mitigating risks associated with climate variability or resource constraints.

India's low per capita renewable energy capacity (0.12 kW) compared to global leaders like Brazil (0.9 kW) and Canada (2.8 kW) highlights a critical challenge for developing nations: ensuring equitable energy access. For populous countries like Bangladesh and Pakistan, where per capita electricity consumption remains low (0.5 kWh and 0.6 kWh per day, respectively), scaling renewable capacity must be paired with efforts to improve distribution and access, particularly in rural areas. India's heavy reliance on grid-connected systems (97–100% across RE sources) limits off-grid solutions, a lesson for Bangladesh, which has successfully deployed solar home systems in rural regions but struggles with grid integration (Debnath et al., 2023). Pakistan faces similar challenges with grid connectivity in remote areas, where off-grid solar and micro-hydropower could bridge gaps (Siraj et al., 2024). Achieving SDG7's target of universal energy access requires investments in decentralized systems and affordable storage technologies to reach underserved populations.

India's experience reveals that challenges such as land acquisition, underdeveloped transmission infrastructure, and high storage costs impede renewable energy scaling. These barriers are particularly relevant for Bangladesh and Pakistan, where land constraints and financial limitations are pronounced. Bangladesh's dense population and limited land availability necessitate innovative solutions like floating solar plants, which India has piloted in states like Kerala (Payel et al., 2023). Pakistan, with its fiscal constraints, could adopt India's model of public-private partnerships to fund RE projects (Kumar and Majid, 2020). Developing nations must also prioritize grid modernization to integrate variable RE sources, addressing SDG7's reliability component by investing in smart grids and energy storage research to mitigate intermittency.

India's position as a regional leader in renewable energy offers opportunities for collaboration with neighbors like Bangladesh and Pakistan. Cross-border knowledge sharing on policy design, technological innovation, and grid management could accelerate RE adoption. For instance, India's expertise in large-scale solar projects could benefit Bangladesh's solar ambitions (Payel et al., 2024), while Pakistan's experience in small-scale hydropower could inform India's underdeveloped micro-hydro sector. Regional initiatives, such as the South Asia Clean Energy Forum, could facilitate technology transfers and joint projects, aligning with SDG7's call for international cooperation to advance clean energy access and innovation.

India's rapid RE expansion has raised concerns about land use and ecological impacts, particularly for solar projects on agricultural land (Ortiz et al., 2022). Bangladesh and Pakistan, with similar land-use pressures, must prioritize strategic site selection to minimize environmental degradation. Community engagement and fair compensation for land use, as seen in some Indian projects, can mitigate social resistance and displacement concerns. This approach supports SDG7's sustainability goal by ensuring that clean energy transitions do not compromise ecological or social equity

5. Conclusion

This study presents a comprehensive assessment of India's renewable energy progress through descriptive statistical analysis using secondary data sourced from IRENA. The findings show that India has achieved remarkable growth in total renewable energy capacity, rising from 25 GW to 176 GW over two decades, and now ranks 4th globally. Solar energy leads the mix, followed by wind and hydro, while bioenergy remains underutilized. Notably, India ranks 3rd in total installed capacity at 505 GW, but lags significantly in per capita metrics, with only 0.12 kW of renewable and 0.35 kW of total installed electricity per person — the lowest among the top 10 renewable-producing countries. Moreover, while the global renewable sector is technologically diverse, India relies heavily on onshore wind, solid biofuel, and photovoltaic solar, with minimal participation in offshore wind, CSP, and mixed hydropower technologies.

These results imply that while India has made substantial progress in scaling up renewable energy, challenges remain in equitable distribution, energy accessibility, and technological diversification. The high share of on-grid capacity is commendable for national grid integration but also reveals a dependence on centralized systems due to high energy storage costs. The country's balanced ranking across solar, wind, hydro, and bioenergy indicates a broad-based renewable strategy, yet significant regional and sectoral disparities persist.

The study's limitations include the use of aggregate national-level data, which may overlook state-wise variations, and reliance on secondary sources, which restrict deeper technical validation. Additionally, descriptive statistics limit the scope for causal inferences or forecasting trends.

Future research can explore region-specific performance, policy effectiveness, and the integration of energy storage systems. It should also examine the socioeconomic impacts of renewable energy adoption, particularly in underserved rural regions. Expanding into underutilized technologies like offshore wind and CSP can further strengthen India's energy mix, supporting its transition to a low-carbon and inclusive energy future.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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