Wind Energy Potential And Deployment Challenges In India: Technical And Economic Perspective

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Abstract- *India's transition toward sustainable energy systems necessitates the effective utilization of its abundant renewable resources. Among these, wind energy presents a significant yet underutilized opportunity, with an estimated potential of approximately 695 GW at higher hub heights, compared to an installed capacity of just over 50 GW as of 2025. This study investigates the disparity between resource availability and actual deployment through an integrated technical and economic perspective. The analysis combines recent literature, national datasets, and graphical evaluations to examine capacity trends, regional distribution, and cost dynamics. The findings indicate that the primary barriers to wind energy deployment are not resource-related but stem from systemic challenges, including grid limitations, financial constraints, and policy inconsistencies. Furthermore, the study highlights the economic dominance of onshore wind and the emerging potential of offshore systems despite their higher costs. The paper concludes that addressing these interconnected challenges through coordinated infrastruc-ture development, policy stability, and technological advancement is essential for unlocking India's wind energy potential.*

Keywords: Wind Energy Deployment, Renewable Energy Sys-tems, Techno-Economic Analysis, Onshore Wind Power, Offshore Wind Energy, Grid Integration, Capacity Utilization Factor (CUF), Levelized Cost of Energy (LCOE), Energy Policy and Regulation, Power Transmission Infrastructure, Wind-Solar Hy-brid Systems, Sustainable Energy Transition, India Energy Sector

I. INTRODUCTION

The global energy landscape is undergoing a transformation due to the need to reduce carbon emissions and ensure energy security [1]. India faces increasing electricity demand while reducing fossil fuel dependence [2].

India possesses wind energy potential of 302 GW at 100 m and 695 GW at 120 m hub height [3]. However, installed capacity has only crossed 50 GW [1], indicating a major gap.

Wind deployment is affected by technical challenges like intermittency and grid instability [7], economic constraints such as capital cost [5], and policy uncertainties [2].

II. LITERATURE REVIEW

Recent research on wind energy in India demonstrates a strong focus on individual dimensions such as resource assess-ment, technological advancements, and policy mechanisms. However, these studies often operate in isolation, limiting a comprehensive understanding of the sector. Studies by Singh (2022) and Kumar (2022) emphasize the role of policy frame-works in shaping wind energy growth, while Sharma (2024) and Natarajan (2025) highlight the extensive onshore and offshore potential across different regions of India. In parallel, Malik (2024) and Madhiarasan (2022) explore the applica-tion of machine learning techniques to improve wind fore-casting accuracy, addressing technical challenges associated with intermittency.Economic analyses, including Maheshku-mar (2025), reveal that capital investment and infrastructure constraints significantly influence project feasibility, whereas Lindvall (2025) highlights the importance of social acceptance in renewable energy deployment. Despite these contributions, a key limitation in the existing literature is the absence of an integrated framework that simultaneously considers technical, economic, and policy dimensions. This study addresses this gap by adopting a multidisciplinary approach to evaluate wind energy deployment in India.

III. METHODOLOGY

This study adopts a multidisciplinary approach to analyze wind energy potential and deployment challenges in India. The methodology consists of the following components:

1. ***Data Collection:****:* Secondary data was collected from national energy reports, research papers (2020–2025), and government sources such as MNRE.
2. ***Graphical Analysis:****:* State-wise wind potential, installed capacity, and growth trends were analyzed using graphical representations.
3. ***Comparative Analysis:****:* A techno-economic comparison between onshore and offshore wind systems was conducted based on parameters such as CAPEX, LCOE, CUF, and payback period.
4. ***Literature Synthesis:****:* Insights from recent research papers were integrated to identify key technical, economic, and policy challenges.

IV. WIND ENERGY POTENTIAL IN INDIA

India possesses substantial wind energy resources; however, the extent of their utilization remains limited. Based on recent assessments, the total onshore wind potential in India is estimated to exceed 695 GW at 120 m hub height, whereas the installed capacity has reached approximately 53–55 GW by 2025. This indicates that less than 10% of the available wind resource has been harnessed, highlighting a significant gap between potential and deployment.

1. ***State-Wise Potential and Installed Capacity****:* The analysis of state-wise data reveals a strong regional disparity in both installed capacity and resource utilization. Among the major wind-producing states, Gujarat exhibits the highest installed capacity of approximately 13.8 GW, accounting for nearly 27% of the total capacity among the selected states. However, its estimated potential of 142.5 GW results in a utilization rate of only 9.68%, indicating considerable scope for further development. In contrast, Tamil Nadu demonstrates the highest utilization efficiency, with an installed capacity of 11.8 GW against a potential of 68.7 GW, corresponding to a utilization rate of approximately 17.18%. This reflects the effectiveness of early adoption, supportive policy frameworks, and established infrastructure in maximizing wind energy deployment. States such as Karnataka and Rajasthan exhibit moderate levels of utilization, with installed capacities of 7.7 GW each and utilization rates of 13.80% and 6.03%, respectively. Despite Rajasthan's high potential of 127.7 GW, its relatively low

   Gujarat, Tamil Nadu, and Karnataka. This concentration leads to regional imbalances in renewable energy development and places additional stress on localized transmission infrastruc-ture. Moreover, a clear distinction is observed between capac-ity leadership and utilization efficiency. While Gujarat leads in total installed capacity, Tamil Nadu demonstrates superior efficiency in utilizing available wind resources. This suggests that effective policy implementation, grid infrastructure, and project execution mechanisms are critical determinants of deployment success.
2. ***Offshore Wind Potential****:* In addition to onshore resources, India possesses considerable offshore wind potential, particu-larly along the western and southern coastlines. Preliminary estimates indicate approximately 36 GW of offshore potential in Gujarat and 35 GW in Tamil Nadu. However, offshore wind development in India remains at an early stage due to high capital costs, technological challenges, and limited supporting infrastructure.
3. ***Key Observations****:* From the above analysis, the following key observations can be drawn:
   1. India has a vast wind energy potential; however, the current utilization remains below 10%.
   2. Wind energy deployment is regionally concentrated, leading to imbalances in infrastructure and resource utilization.
   3. There exists a significant gap between high-potential states and their actual deployment levels, particularly in Rajasthan and emerging regions.
   4. Policy effectiveness and infrastructure availability play a more decisive role than resource availability in deter-mining utilization efficiency.

A. State-wise Analysis

TABLE I
State-wise Wind Energy Data
State Installed (MW) Share Potential (GW) Utilization Gujarat
13800 27% 142.5 9.68%
Tamil Nadu 11800 23% 68.7 17.18%

utilization suggests the presence of infrastructural and policy constraints. Further, Maharashtra and Andhra Pradesh	Karnataka Raj asthan Maharashtra	7700 7700 5200	15% 15% 10%	55.8 127.7 98.2	13.80% 6.03% 5.30%

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comparatively lower utilization levels, approximately 5.30% and 5.34%, respectively, despite possessing moderate wind	Andhra Pradesh Others	4000 1000	8% 2%	74.9 127.7	5.34% 0.78%

potential. This indicates that factors beyond resource availabil-ity—such as grid connectivity, land acquisition, and regulatory processes—play a critical role in determining deployment levels. The "Others" category, representing emerging wind regions, exhibits a substantial potential of 127.7 GW but an installed capacity of only 1 GW, resulting in a utilization rate of less than 1%. This highlights the presence of significant untapped wind corridors across the country.

2. ***Utilization Trends and Regional Disparities****:* The com-parative analysis indicates that wind energy deployment in India is highly concentrated in a few states, particularly

Tamil Nadu shows highest efficiency, while Gujarat leads in capacity.

B. Offshore Potential

India has 36 GW potential in Gujarat and 35 GW in Tamil Nadu, though still underdeveloped.

V. HISTORICAL GROWTH (2000–2025)

In addition to the assessment of potential and current deploy-ment, it is essential to analyze the historical growth trajectory of wind energy in India, which provides insights into the sec-tor's evolution and future scalability. The cumulative installed wind power capacity in India has grown from approximately 1.2 GW in 2000 to over 50 GW by 2025, representing a significant expansion over the past two and a half decades. This growth reflects the gradual transition of wind energy from a niche technology to a major contributor in the national energy mix.

1. A closer examination of the growth pattern reveals three distinct phases:*:*

1.1 Initial Development Phase (2000–2010): During this period, the wind energy sector experienced steady but moderate growth, driven primarily by early policy in-centives and pilot-scale installations. The average annual capacity addition remained relatively low, reflecting lim-ited technological maturity and infrastructure.

1.2 Expansion Phase (2010–2020): The sector witnessed accelerated growth, with annual capacity additions aver-aging approximately 2.4–2.5 GW per year. This phase was marked by improved turbine technologies, increased private sector participation, and enhanced policy support. By 2010, India had already emerged as one of the top wind energy markets globally.

1.3 Stabilization and Transition Phase (2020–2025): In recent years, the growth rate has remained consistent, with average annual additions of around 2.4–3 GW, followed by a notable increase in 2025. This period reflects a transition toward a more competitive and mature market structure, influenced by auction-based bidding mechanisms and integration with hybrid renew-able systems.

2. The long-term growth trend highlights several important insights:*:*

2.1 The wind energy sector has demonstrated consistent and sustained expansion, despite fluctuations in policy and market conditions.

2.2 The increase in annual capacity additions post-2010 indicates a shift toward industrial-scale deployment and technological maturity.

2.3 The ability to maintain steady growth even under com-petitive market conditions reflects the resilience and adaptability of the sector.

However, when compared with the total available potential, the growth trajectory also emphasizes that the current rate of deployment is insufficient to fully exploit India's wind resources within the desired time frame.

3. Integrated Perspective*:* While historical growth indicates strong progress, it simultaneously underscores the persistent gap between potential and actual deployment. The transition from early-stage development to a mature market has been achieved; however, the pace of expansion must accelerate significantly to align with the country's renewable energy targets.

TABLE II
Onshore vs Offshore Comparison

Metric	Onshore	Offshore
CAPEX (Cr/MW)	7.5	23
LCOE (/kWh)	3.3–3.8	8–10
Payback (Years)	7	13.5
CUF (%)	30	50

VI. ECONOMIC ANALYSIS

The economic feasibility of wind energy projects in India is a critical determinant of large-scale deployment. Based on the comparative analysis of onshore and offshore wind systems, significant differences are observed in terms of capital investment, operational efficiency, and long-term returns.

1. ***Capital Expenditure and Cost of Energy****:* The capital expenditure (CAPEX) for onshore wind projects in India is estimated to be approximately 7.5 crore per MW, whereas offshore wind projects require substantially higher investment, around 23 crore per MW. This indicates that offshore in-stallations demand nearly three times the initial investment compared to onshore systems. Similarly, the Levelized Cost of Energy (LCOE) further highlights this disparity. Onshore wind energy exhibits a relatively lower cost of approximately 3.3–3.8 per kWh, making it competitive with other renewable sources. In contrast, offshore wind energy has a significantly higher LCOE in the range of 8–10 per kWh, primarily due to higher installation, infrastructure, and maintenance costs.
2. ***Capacity Utilization and Efficiency****:* Despite higher costs, offshore wind systems demonstrate superior operational per-formance. The Capacity Utilization Factor (CUF) for offshore wind projects is approximately 50%, compared to 25–35% for onshore wind. This increased efficiency is attributed to stronger and more consistent wind speeds over oceanic re-gions. However, the higher CUF does not fully offset the increased capital and operational costs, particularly in the current stage of technological and infrastructural development in India.
3. ***Payback Period and Economic Viability****:* The payback period serves as a key indicator of investment viability. On-shore wind projects typically achieve cost recovery within 6–8 years, whereas offshore wind projects require a significantly longer period of approximately 12–15 years. This extended payback duration, combined with high upfront costs, makes offshore wind less attractive for immediate investment in the Indian market. Consequently, onshore wind remains the more economically viable option for short- to medium-term deployment.
4. ***Operation and Maintenance Costs****:* Operational and main-tenance (O&M) costs further differentiate the two systems. Offshore wind projects incur substantially higher annual main-tenance expenses due to harsh marine conditions, including corrosion, accessibility challenges, and specialized equipment requirements. Annual OPEX for offshore systems is estimated to reach up to 1.2 crore per turbine, which is more thandouble that of onshore wind systems. These additional costs significantly impact the overall lifecycle economics of offshore wind projects.
5. ***The comparative analysis reveals a clear trade-off be-tween efficiency and cost:****:*
    1. Offshore wind offers higher efficiency and energy output due to better wind conditions.
    2. Onshore wind provides lower capital investment, re-duced LCOE, and shorter payback periods.
    3. wind remains economically challenging under current conditions due to high CAPEX and OPEX requirements.
6. ***Key Observations****:* The following observations can be drawn from the economic analysis:
    1. Onshore wind energy currently represents the most cost-effective and financially viable option for large-scale deployment in India.
    2. Offshore wind, while technologically promising, re-quires substantial policy support, financial incentives, and infrastructure development to become competitive.
    3. The economic gap between onshore and offshore wind highlights the need for phased development strategies, focusing on cost reduction and technological advance-ments.

VII. CHALLENGES AND BARRIERS IN WIND ENERGY DEPLOYMENT IN INDIA

Despite the significant wind energy potential in India, its large-scale deployment remains constrained by a combination of technical, economic, and policy-related barriers. These challenges are interdependent and collectively contribute to the gap between estimated potential and actual utilization.

1. ***Technical Barriers****:* One of the primary technical chal-lenges in wind energy deployment is the intermittent and variable nature of wind resources, which leads to fluctuations in power generation. This intermittency affects grid stability, resulting in issues such as voltage variations, frequency de-viations, and reduced reliability of power supply. In addition, the inadequate transmission infrastructure in wind-rich regions poses a significant constraint. Many high-potential areas, par-ticularly in states such as Rajasthan and Gujarat, are located far from load centers, leading to difficulties in efficient power evacuation. This often results in curtailment of wind power, where generated energy cannot be fully

utilized. Another critical limitation is the lack of advanced forecasting and grid integration mechanisms. Although recent advancements in machine learning and artificial intelligence have improved wind prediction accuracy, their large-scale implementation in India remains limited. Furthermore, aging wind turbines with lower capacity ratings contribute to reduced efficiency and highlight the need for repowering strategies.

2. ***Economic Barriers****:* From an economic perspective, wind energy projects—particularly offshore installations—are char-acterized by high initial capital investment requirements. As discussed in the previous section, offshore wind projects require nearly three times the capital expenditure of onshore systems, making them less attractive for private investors. Additionally, the financial viability of wind projects is af-fected by delayed payments from distribution companies (DIS-COMs), which create cash flow uncertainties for developers. The declining tariff trends due to competitive bidding mech-anisms further compress profit margins, discouraging new investments. Operation and maintenance costs, especially for offshore wind systems, add to the economic burden. The high OPEX associated with marine environments increases lifecycle costs and extends payback periods. These factors collectively reduce the attractiveness of wind energy projects, particularly in comparison to solar energy, which currently offers lower costs and faster returns.
3. ***Policy and Regulatory Barriers****:* Policy and regulatory challenges also play a crucial role in limiting wind energy deployment. Frequent changes in government policies and auction mechanisms introduce regulatory uncertainty, which affects long-term investment planning. Land acquisition and environmental clearance processes often lead to project delays, particularly in densely populated or ecologically sensitive regions. The absence of streamlined approval mechanisms increases project timelines and costs. Furthermore, inconsis-tencies in state-level policies and incentives create disparities in wind energy development across regions. While some states have established supportive frameworks, others lack adequate policy support, leading to uneven growth.
4. ***Integrated Perspective of Barriers****:* A key insight from this study is that the challenges in wind energy deployment are not isolated but highly interconnected. Technical limitations such as grid constraints directly impact economic viability by causing power curtailment and revenue losses. Similarly, policy uncertainties influence financial risks, which in turn affect investment decisions and technological adoption. This interdependence creates a systemic barrier, where progress in one domain is dependent on improvements in others. For instance, enhancing grid infrastructure without addressing policy or financial constraints may not result in significant deployment growth.
5. ***Key Observations****:* The following observations summarize the major challenges: Technical barriers such as intermittency and weak grid infrastructure limit reliable power generation and evacuation. Economic challenges, including high capital costs and financial risks, reduce investor participation. Policy and regulatory uncertainties hinder project execution and long-term planning. The combined effect of these factors creates a significant gap between wind energy potential and actual deployment in India.

VIII. CONCLUSION

The findings of this study clearly demonstrate that India's wind energy sector is characterized by a substantial gap between potential and actual utilization. While the country has made significant progress in capacity expansion, the current deployment levels do not reflect the magnitude of available resources.

The analysis indicates that this gap is primarily driven by interconnected technical, economic, and policy challenges rather than limitations in resource availability. Addressing these challenges requires a holistic approach that aligns infras-tructure development, financial mechanisms, and regulatory frameworks.

With appropriate interventions, wind energy has the potential to play a transformative role in India's energy transition, contributing to sustainability, energy security, and long-term economic growth.

IX. FUTURE SCOPE

To fully unlock the potential of wind energy in India, several strategic developments must be prioritized in the coming years. Strengthening transmission infrastructure and adopting smart grid technologies can significantly improve power evacuation and grid stability in wind-rich regions [19]. In addition, focused investments in offshore wind infrastructure, supported by favorable government policies and financial incentives, can help utilize the vast coastal wind resources available in states such as Gujarat and Tamil Nadu [4].

The integration of wind–solar hybrid systems presents another promising direction for improving energy reliability and re-ducing intermittency issues [15]. Furthermore, the adoption of advanced technologies such as artificial intelligence and machine learning for wind forecasting, predictive maintenance, and grid management can enhance operational efficiency and reduce system losses [7], [8], [9].

Repowering older wind turbines with modern high-capacity systems can also improve energy output without requiring additional land resources [5]. At the policy level, stable regulatory frameworks, timely payments by DISCOMs, and improved investment mechanisms are essential for increasing investor confidence and accelerating deployment [2]. Finally, exploring underutilized wind corridors across emerging re-gions of India can contribute toward a more balanced and sustainable renewable energy ecosystem.

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