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HARNESSING WIND POWER FOR INDUSTRIAL SUSTAINABILITY IN GREATER KOLKATA: A LOW-CARBON CIRCULAR ECONOMY PERSPECTIVE

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ABSTRACT

The deployment of wind energy in industrial zones with low to moderate wind potential, such as those surrounding Kolkata, West Bengal, presents an underexplored yet promising opportunity for sustainable development. This research paper develops a spatially explicit framework for integrating wind energy into industrial landscapes of Greater Kolkata, emphasizing circular economy principles and low-wind-speed feasibility. This study also evaluates the feasibility of integrating wind energy into these zones to foster a low-carbon circular economy. We also propose advanced low-wind-speed turbines bladeless oscillation-based systems, for grid stability in the region. The authors also propose a GIS-based GETC model—encompassing Geospatial, Environmental, Technical, and Circularity dimensions—guides site selection across peri-urban clusters. To assess circularity, a novel Circular Economy Performance Index (CEPI) is introduced. The CEPI–GETC integration enables landscape-level planning that aligns technical viability with material recovery and policy compliance.

Results highlight optimal zones for turbine deployment, reverse logistics strategies for blade waste, and policy pathways for embedding circularity in regional energy infrastructure. Comparative analysis with solar energy and lifecycle cost assessments inform investment strategies. The framework supports landscape-level decarbonization and contributes to sustainable industrial transitions in emerging economies. Furthermore, the study explores innovative recycling techniques for decommissioned wind turbine components, including microwave-assisted chemical processes using eco-friendly solvents to recover glass fibers—Enhancing circularity outcomes in wind energy systems. While existing literature emphasizes high-wind regions, this research shifts the narrative toward developing economies, examining lifecycle sustainability from installation to decommissioning. By incorporating regional policy frameworks such as West Bengal's Renewable Energy Policy and showcasing collaborative case studies, the study showcases the importance of stakeholder engagement in fostering a sustainable industrial landscape (Rediff News, 2025). This holistic approach expands the discourse on wind energy viability in suboptimal wind conditions and offers replicable strategies for renewable energy integration in emerging industrial contexts (SENEDS, n.d.).

Keywords: Wind Energy Integration; Industrial Sustainability; Low-Carbon Economy; Circular Economy; GIS-based site selection; Circular economy performance index (CEPI)

INTRODUCTION

The escalating concerns over climate change and environmental degradation have intensified the global shift towards renewable energy sources. Wind energy, characterized by its sustainability and minimal carbon footprint, stands out as a pivotal solution. India has around 45 gigawatts (GW) of onshore wind energy capacity, making it the fourth largest country in the world in terms of total installed wind power capacity as of January 2024. Following China, this places India as the second-largest wind market in the Asia-Pacific area. However, the distribution of this capacity is uneven, with states like Tamil Nadu, Gujarat, and Maharashtra leading the way. West Bengal's contribution remains modest, primarily due to its geographical and climatic conditions. (climatesamurai.com; Bhushan *et al.*, 2019) India holds high aspirations for the development of wind energy in the future. According to the National Electricity Plan, the nation's installed wind capacity will be 73 GW by 2026–27 and 122 GW by 2031–32.

The industrial belt along the Hooghly River, encompassing districts such as Kolkata, Howrah, Hooghly, and parts of North and South 24 Parganas, is one of India's oldest and most significant industrial zones. This region hosts a diverse array of industries, including jute, textiles, heavy engineering, leather, and information technology. The concentration of such industries results in substantial energy consumption, underscoring the need for sustainable and efficient energy solutions. Integrating wind energy into the industrial regions around Kolkata involves several considerations:

Recent studies and institutional reports underscore the growing feasibility of wind energy deployment in urban and peri-urban regions of West Bengal, including Greater Kolkata. A technical review by Mahela & Shaik (2016) provides a comprehensive overview of grid-interfaced wind energy systems, offering insights into turbine control, grid stability, and hybrid integration strategies applicable to low-wind zones like Kolkata Complementing this, Ganvir *et al.* (2022) propose spiral wind turbine designs optimized for variable wind speeds, which are particularly suited for dense urban environments Regionally, the West Bengal Renewable Energy Development Agency (WBREDA) has initiated wind-diesel hybrid projects in coastal areas and continues to support wind energy expansion in semi-urban zones (WBREDA). Furthermore, policy analyses suggest that West Bengal has the potential to become a national leader in renewable energy, with wind power playing a strategic role in industrial sustainability (The Plurals News Network, 2024). In some highly relevant recent studies, Basack *et al.* (2025) investigated the integration of a rooftop vertical-axis wind turbine into urban Kolkata settings through experimental testing and numerical modelling. The results show promising efficient energy generation at low wind speeds, and demonstrated strong correlation between experimental data and CFD simulations using ANSYS FLUENT. Basack *et al.* (2022) also presented experimental and theoretical analyses of a small-scale vertical-axis wind turbine driven by artificial wind to assess performance and vibration behaviour in Kolkata region. The results showed increasing power output with shaft speed and successful operation of an automatic drip irrigation system, confirming the turbine's practical applicability in renewable energy solutions. Podder *et al.* (2024, 2025) explored the potential of vertical axis wind turbines (VAWTs) for small-scale energy generation, highlighting their relevance in promoting industrial sustainability in Greater Kolkata. Their research papers demonstrated how localized wind power solutions can reduce carbon emissions and support a circular economy by integrating renewable energy into domestic and light industrial use, aligning with low-carbon development goals for the region.

Site Selection and Wind Resource Assessment

Conducting comprehensive wind resource assessments is crucial to identify suitable locations for wind turbine installations. Factors such as wind speed, direction, consistency, land availability, and proximity to industrial energy consumers play a significant role in site selection. The precise evaluation of wind resources and the careful selection of appropriate locations are essential to the success of wind energy projects. The first step in this procedure is the gathering and analysis of meteorological data, usually spanning at least a year, in order to assess wind characteristics such as average wind speed, wind direction, turbulence intensity, and diurnal/seasonal fluctuation. For the purpose of utility-scale wind power development, wind speeds of at least 6 m/s at turbine hub height are generally regarded as financially viable (Manwell *et al.*, 2010).

It is also crucial that the wind consistency in both direction and speed is essential. The mechanical tension on turbines is decreased in locations with a prevailing wind direction because of less yawing, which improves operational efficiency and extends lifespan. Turbulence, which is particularly pronounced in complicated landscapes or close to obstacles, should be kept to a minimum since it might raise wear and lower performance. Equally important are geographical and logistical factors such as land availability, land use restrictions, environmental sensitivity (e.g., avian migration routes, noise restrictions), and proximity to current grid infrastructure or industrial energy consumers. Areas closer to transmission lines and major energy users (like data centers or factories) are favoured because they lower transmission losses and infrastructure expenses. Remote sensing technologies such as LiDAR and SoDAR also offer accurate wind measurements at different altitudes, improving the accuracy of resource assessments. These tools provide high-resolution, vertically resolved wind profiles at various altitudes, capturing local wind speed and direction with accuracy. LiDAR and SoDAR are effective in both urban and mountainous terrains, revealing complex wind patterns and twist angles, while radar wind profilers offer reliable data for boundary layer studies and weather prediction assessments and are quite accurate in their results (Song *et al.*, 2020; Tamura *et al.*, 2001). Manwell, McGowan, and Rogers (Manwell *et al.*, 2010), in their book Wind Energy explained, highlight the importance of integrating meteorological, environmental, and economic considerations when selecting a site, pointing to the multidisciplinary nature of wind energy planning.

Technological Adaptations

Given the moderate wind speeds in West Bengal compared to other regions, selecting wind turbines designed for low-wind-speed conditions is essential. Advances in turbine technology has led to the development of models capable of operating efficiently in such environments (Venkatramakrishnan *et al.*, 2010). For instance, Vestas introduced the V155-3.3 MW wind turbine, specifically developed for low and ultra-low wind conditions in India. This turbine features a larger rotor area, enhancing energy capture in regions with moderate wind speeds. Similarly, GE launched the 1.7-103 wind turbine, engineered for India's low-wind-speed conditions, offering a 30 % increase in annual energy production compared to its predecessor (https://shorturl.at/74suO). These innovations reflect the industry's commitment to optimizing wind energy generation in areas with moderate wind resources. Moreover, research indicates that wind turbines designed for low-wind-speed areas often have larger rotor diameters and higher hub heights to maximize energy capture. This design approach aligns with the wind resource classification system, where turbines for low-wind-speed areas are categorized as Class III, emphasizing the need for specialized designs to enhance performance in such conditions. (Yang *et al.*, 2018).

Grid Integration and Energy Storage

Effective integration of wind energy into the existing power grid requires robust infrastructure to manage variability and ensure a stable power supply (Ahmed *et al*., 2020). Implementing energy storage solutions (ESS) may help mitigate intermittency issues and provide reliable energy to industrial operations (Durgadevi *et al*., 2024). Integrating energy storage systems (ESS) with wind power conversion systems enhances grid stability by mitigating the fluctuations in power output, such as battery energy storage systems (BESS) and flywheels, can also smooth out the variability of wind energy, ensuring a consistent power supply. These systems provide ancillary services like frequency and voltage regulation, which are crucial for maintaining grid reliability. By providing backup power during outages and supporting grid operations during disturbances, ESS contribute to a more resilient and reliable energy infrastructure (Ullah *et al*., 2024).

Circular Economy in Wind Energy

Circular economy models in the wind industry aim to narrow, slow, and close resource loops, generating economic and social benefits (IEA Wind TCP, 2026) while improving environmental performance. These models are supported by frameworks such as the Ellen MacArthur Foundation's Circularity Indicators, which offer metrics to assess material recovery, reuse, and lifecycle efficiency (Ellen MacArthur Foundation, n.d.). These models focus on technology innovation at various levels, including materials, components, and products, to support sustainable wind energy infrastructure (Mendoza *et al*., 2022). The integration of circular economy strategies into wind energy can lead to more resource-efficient and sustainable systems (Velenturf, 2021). The evaluation framework aligns with international standards for circular economy monitoring, including the UNECE Guidelines for Measuring Circular Economy (United Nations Economic Commission for Europe, 2024).

Table 1: Technological Adaptations for Low-Wind-Speed Regions (Adapted from Vestas, GE, Oswal, 2018)

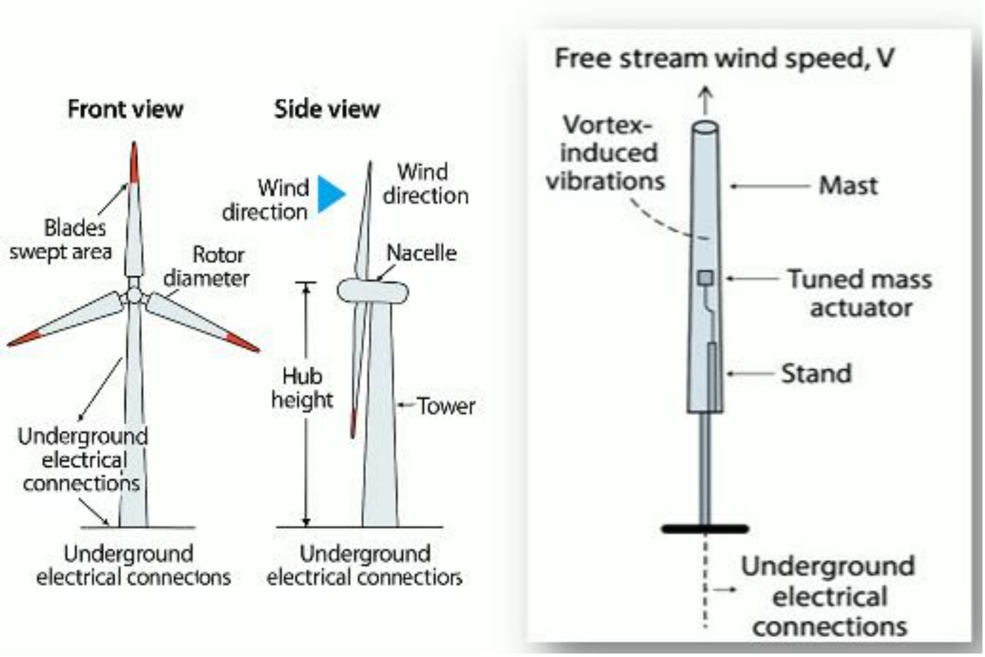
Technology	Purpose
Larger Rotors	Capture more wind in low-speed areas
Bladeless Turbines	Low-maintenance oscillation-based
Energy Storage	Manage supply fluctuations

Table 1 address the technological adaptations address the challenges of low-wind-speed regions.

Different Design strategies

Larger Rotors: Larger rotor diameters in wind turbines increase the swept area, enabling turbines to capture more wind energy, especially in regions with lower wind speeds. Increasing rotor diameter expands the swept area, allowing turbines to harness more wind energy. This is particularly beneficial at sites with lower average wind speeds, as more energy can be captured even when the wind intensity is less (Ribnitzky *et al*., 2024). The primary advantage of larger rotors is not higher efficiency, but the ability to intercept more wind, resulting in greater energy production and improved capacity factors. Larger rotors can achieve higher tip-speed ratios and thrust loads, which contribute to better aerodynamic efficiency and higher power output at lower wind speeds (Ribnitzky *et al*., 2024; Bilgili *et al*., 2021). Bladeless Turbines: These turbines use oscillation-based mechanisms instead of traditional blades, reducing mechanical complexity and maintenance costs. Bladeless turbines have fewer moving parts—often just a single oscillating mast—eliminating the need for blades, gears, and bearings. This results in lower maintenance costs and increased reliability compared to conventional turbines (Oswal, 2018). Their design minimizes noise and environmental disruption, making them ideal for areas with ecological or residential constraints. In Fig. 1 we can find the comparative schematic of two wind energy technologies: (Left) Horizontal Axis Wind Turbine (HAWT) with larger rotors mounted on a nacelle atop a tall tower, optimized for high-wind-speed regions and utility-scale deployment; (Right) Vertical Axis Bladeless Turbine (VAWT) utilizing vortex-induced vibrations and a tuned mass actuator system for energy conversion, suitable for low-wind-speed environments and urban-industrial integration. Both designs include underground electrical connections, highlighting infrastructure considerations in circular energy planning. The absence of rotating blades significantly reduces noise pollution and vibration, making these turbines ideal for use in noise- sensitive environments. They also minimize risks to birds and do not interfere with radio waves (Panda *et al.*, 2018).

Fig. 1: Comparison of wind turbine designs: (Left) Horizontal Axis Wind Turbine (HAWT) with large rotors mounted on a nacelle; (Right) Vertical Axis Bladeless Turbine (VAWT) utilizing vortex-induced vibrations and a tuned mass actuator



Energy Storage Systems: Advanced storage technologies, such as lithium-ion batteries and pumped hydro storage, help manage intermittent wind energy supply. These systems store excess energy during high wind periods and release it during low-demand times, ensuring a steady energy supply. Lithium-Ion Batteries absorb excess wind energy during periods of high generation and release it during low wind or high demand, providing rapid response to short- term fluctuations. Integrated with wind turbines, they smoothen power output, stabilize voltage and frequency, and improve power quality at the grid connection point (Behabtu *et al.*, 2023). As per pumped hydro storage is concerned, they store surplus wind energy by pumping water to a higher elevation during excess generation, then releases it to generate electricity when needed, handling larger-scale and longer-duration fluctuations (Wu *et al.*, 2024). It is also traditionally used for grid balancing and ancillary services, especially effective for managing significant power imbalances (Immendoerfer *et al.*, 2017).

Wind Energy Modelling

Potential Assessment and power output

The power output of a wind turbine (Pw) is a function of wind speed (V), air density (ρ), the swept area of the turbine blades (A), and the power coefficient (C_p), which reflects the aerodynamic efficiency of the turbine. The relationship is given by:

$$P_w=1/2\rho AC_pV^3 \qquad (1)$$

In industrial zones characterized by low-wind-speed conditions, optimizing Cp and the blade pitch angle (θ) becomes crucial for maximizing Pw. The efficiency of the overall system (η) also includes losses in conversion and transmission and plays a critical role in determining the total energy output over time (Et).

Energy Output and Efficiency Modelling

To evaluate the practical energy generation over a given time period, the total energy output (E_t) we can calculate it by integrating power output (P_w) over operational hours. Turbine efficiency (η) can be included to account for losses during conversion and transmission. The model was calibrated for low-wind-speed conditions, which are prevalent in the region. Energy storage requirements (E_s) were assessed based on the gap between generation and real- time demand (Ed), taking into account load patterns of local industries Energy Statistics India 2025 (AGGRP, 2025).

Grid Integration and Capacity Evaluation

Wind energy can be modelled by the capacity of the existing grid infrastructure to integrate new renewable energy sources. The maximum permissible load addition was represented by Gi, and simulations were run to assess grid reliability and stability under varying wind energy penetration levels. Recommendations for infrastructure upgrades and smart grid technologies were also developed.

Carbon Emission Reduction Estimation

Environmental benefits can be quantified by estimating reductions in carbon dioxide emissions (ΔCO_2). The baseline emissions (CO_2) from fossil fuel-based energy sources were compared to projected emissions after wind energy integration. The calculation also factored in the regional energy mix and projected industry growth.

$$\Delta CO_2=CO_{2,\text{baseline}}-CO_{2,\text{post-integration}} \qquad (2)$$

To address energy demand (Ed) in industrial regions, stored wind energy (Es) must be efficiently managed. This necessitates advanced energy storage solutions to compensate for the intermittent nature of wind. Additionally, assessing the grid integration capacity (Gi) ensures that the electrical infrastructure can accommodate increased renewable energy influx without compromising reliability. One of the major benefits of wind energy is the potential for carbon dioxide (CO_2) emission reductions. The difference between current emissions and those post-integration is represented as ΔCO_2. This value quantifies the environmental impact and supports the case for policy interventions and subsidies under schemes such as West Bengal's Renewable Energy Policy (https://surl.li/kjbbtw) Wind power projects have very low life-cycle carbon intensities, typically around 4.4 g CO_2/kWh for onshore projects and 0.13 kg CO_2-eq/MJ for offshore turbines, which is much lower than coal-fired power plants. Over their lifetimes, wind projects can reduce millions of tons of CO_2 emissions compared to coal, with one case study showing a potential reduction of 2.04 million tons for a 49.5 MW project (Jinying *et al.*, 2020). A crucial aspect of circular economy integration is the recycling rate of wind turbine components (R_r), particularly after their decommissioning time (T_d) expires. This study also highlights innovative methods such as microwave-assisted chemical recycling, which can recover glass fibers from turbine blades using eco-friendly reagents, enhancing sustainability.

Wind turbine blade, waste management and circular economy strategy

The management of wind turbine blade waste is a significant challenge, with various strategies being explored to optimize material recovery. Techniques such as solvolysis and pyrolysis are being evaluated for their circular economy performance and carbon footprint, with solvolysis identified as a particularly effective method (Diez-Cañamero *et al.*, 2023). The development of sustainable decommissioning practices and circular options for end-of-life wind turbine blades is crucial for reducing environmental impacts (Tyurkay *et al.*, 2024).

The wind industry also faces challenges in implementing circular economy strategies, including the need for efficient reverse logistics, improved recycling technologies, and the development of circular wind hubs for information sharing (Mendoza & Pigosso, 2023). The offshore wind sector, in particular, requires a holistic approach to integrate circular economy strategies throughout the lifecycle of wind energy infrastructure. Circular economy approaches aim to maximize resource use, minimize waste, and ensure sustainability from design to decommissioning. Effective circularity requires strategies embedded at every stage: design, development, operation, maintenance, and end-of-use management (Velenturf, 2021). Eighteen strategies have been identified, including design for circularity, modularization, maintenance, reuse, refurbishment, lifetime extension, repowering, decommissioning, disassembly, recycling, and energy recovery (Gode & Aspelund, 2024). Policy and regulatory factors play a significant role in the development of circular economy strategies in the wind industry. There is a need for comprehensive guidelines to drive legislative, industrial, and academic actions to support the transition to a circular economy. The market uptake of circular business models and the deployment of integrated renewable energy systems are also critical for achieving sustainability goals (Mendoza *et al.*, 2023).

Further research is needed to explore the potential of circular economy strategies in the wind industry, particularly in areas such as lifetime extension, reuse, and recycling (Shafiee, 2024)

Table 2: Installed renewable energy capacity in India (as of March 2024). Source: Ministry of New and Renewable Energy (MNRE), 2024 (https://mnre.gov.in/en/renewable-energy-statistics/).

State / MW	2020	2021	2022	2023	2024
Gujarat	12,368	13,000	13,500	14,000	14,500
Tamil Nadu	9,000	9,200	9,400	9,600	9,800
Maharashtra	5,216	5,300	5,400	5,500	5,600
Rajasthan	5,195	5,300	5,450	5,600	5,750
Karnataka	6,724	6,800	6,900	7,000	7,100
Andhra Pradesh	4,096	4,200	4,300	4,400	4,500
West Bengal	~2	~2	~2	~2	~2

The development of integrated circularity and sustainability studies can provide methodological recommendations for sustainable industrial innovation. The transferability of circular economy frameworks to other energy sectors, such as oil and gas and onshore wind, offers opportunities for broader application and impact. The integration of sustainable energy within a circular economy can contribute to achieving climate and emission neutrality (Klemeš *et al.*, 2023).

Wind Energy Potential in West Bengal

Assessing the wind energy potential in West Bengal is crucial for integrating wind power into the state's energy mix. Historically, wind energy development in India has been concentrated in states with high wind speeds. West Bengal, with its moderate wind profiles, has seen limited development in this sector.

The state's Wind Energy Programme initiated projects like the 2 MW wind farm at Fraserganj in 2002. However, this project suffered damage during Cyclone Amphan in 2020 and has been non-operational since (nres.wb.gov.in).

The Table 2 summarizes the installed wind power capacity in top Indian states, including West Bengal, from 2020 to 2024 based on available data: West Bengal's wind power capacity remains minimal compared to other states, as its wind energy potential is relatively low (Ministry of New and Renewable Energy, n.d.). However, states like Gujarat and Tamil Nadu lead the way in wind energy installations.

Fig. 2 and 3 gives an idea of wind installation and speeds in different states of India (https://seneds.com/wind-energy-in-west-bengal/), West Bengal's average wind speeds are generally lower compared to states like Tamil Nadu, Gujarat, or Rajasthan, which are known for their high wind energy potential. Coastal areas in West Bengal, such as Purba Medinipur, experience relatively higher wind speeds, but they still fall short of the optimal levels required for large-scale wind energy projects in perspective of wind power feasibility and sustenance in terms of energy.

Fig. 2: Installed Wind power capacity

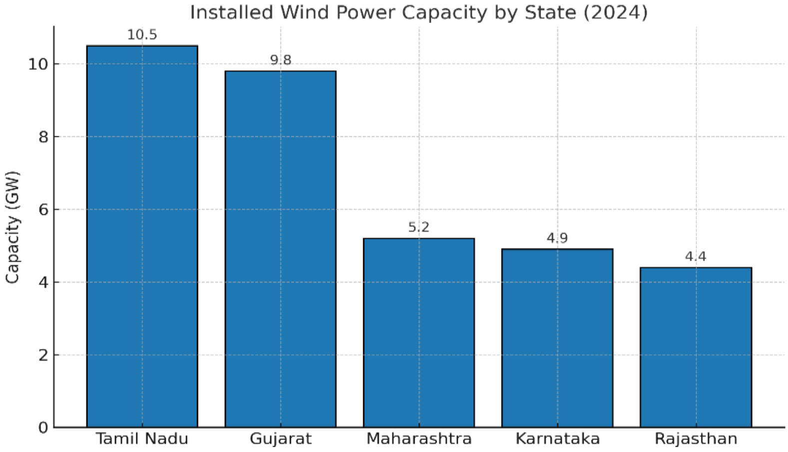
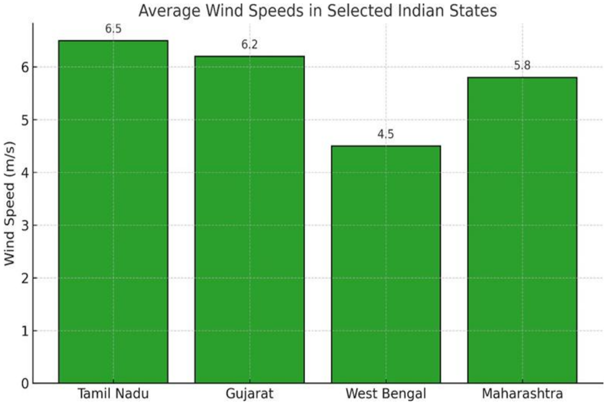


Fig. 3: Average wind speeds as compared to West Bengal



Motivation of the Research

This study proposes a novel framework for integrating wind energy into the industrial zones of Greater Kolkata, addressing a critical gap in region-specific renewable energy planning within emerging economies. The Geographic–Economic–Technical Convergence (GETC) model uniquely combines geographic wind potential, industrial energy demand, and economic constraints, offering a multidimensional approach that surpasses conventional single-focus models.

To evaluate feasibility, the framework incorporates the Circular Economy Performance Index (CEPI), assessing recyclability, cost efficiency, and carbon reduction—pioneering the linkage between renewable energy integration and circular economy principles, an area often overlooked in energy infrastructure research aligned with standardized circularity metrics such as ISO 59020 (International Organization for Standardization, 2024).

We further present a case study through the Dual-District GIS Dashboard: Howrah & Hooghly (2025 Prototype), a GIS-integrated assessment tool that maps wind energy potential, pollution intensity (CEPI), demographic trends, energy demand, and transport load for these key industrial districts in West Bengal, India (NITI Aayog, n.d.). This prototype supports strategic planning under the state's renewable energy roadmap and delivers actionable insights for embedding circular economy strategies and mitigating industrial pollution. By integrating spatial analytics with sustainability metrics, the dashboard offers policymakers and industry stakeholders a data-driven foundation for targeted interventions.

Despite these advancements, key research gaps remain: empirical validation through real-world implementation, alignment with policy and regulatory frameworks, scalability to other regions or energy sources, and deeper exploration of social and institutional factors influencing industrial adoption. The study also introduces innovative recycling methods for turbine components, providing a blueprint for lifecycle sustainability in developing economies. Collectively, these contributions advance wind energy adoption in industrial regions with moderate wind conditions. To the authors' knowledge, no prior literature addresses wind power for industrial sustainability in Greater Kolkata from a low-carbon circular economy perspective—integrating resource efficiency, waste minimization, and material reuse to enhance sustainability and reduce emissions.

METHODOLOGY FOR THE STUDY

The study combined qualitative and quantitative methods to engage a diverse set of stakeholders across West Bengal.

Data Collection Procedures

Site-Level Data Collection

A geospatial mapping exercise identified optimal locations for wind installations.

1. GIS Analysis
    - Overlay wind speed maps with grid infrastructure layers.
    - Mark proximity to high-demand industrial energy consumers.
2. Terrain and Land Use
    - Classify land availability using satellite imagery.
    - Flag protected or ecologically sensitive zones for exclusion.

Policy and Technical Review

A thorough review of national guidelines and standards ensured regulatory compliance (National Institute of Wind Energy, n.d.).

- MNRE Guidelines
    - Evaluated protocols for prototype installations, grid synchronization, and RLMM listings.
    - Cross-checked with NIWE implementation procedures.
- BIS ETD 42 Standards
    - Reviewed sectional committee reports and alignment with IEC/IECRE for certification and testing.

CEPI Dashboard Development

The Circular Economy Performance Index (CEPI) offered a composite metric for project sustainability.

1. Data Sourcing
    - GHG intensities by lifecycle stage Badea & Vlad (2025)
    - Material breakdown from Vestas V163-4.5 MW LCA report. [https://shorturl.at/PGP4n]

SCOPE FOR DEVELOPMENT IN WEST BENGAL'S RENEWABLE ENERGY POLICY

Current Policy Snapshot

West Bengal's Renewable Energy Policy, enacted in 2012 (West Bengal Renewable Energy Policy Document (West Bengal Green Energy Development Corporation Limited, 2012); WBREDA Policy Overview) prioritizes co-generation and electricity generation from renewable sources by setting targets for decentralized generation, land allocation, financial incentives, and regulatory support (West Bengal New and Renewable Energy Development Agency, n.d.). While it laid important groundwork for solar, biomass, and small hydro, the policy predates advances in low-wind-speed turbine technologies, bladeless systems, and modern storage solutions. It also lacks provisions for circular economy integration—such as blade recycling or lifecycle sustainability metrics—and does not address climate-resilient infrastructure. Consequently, the state's renewable share remains below national ambitions, and industrial zones with moderate wind resources remain underutilized.

Identified Gaps & Development Opportunities

Six critical gaps highlight pathways for policy enhancement which follows from DST-CPR Report on Energy Transition in West Bengal (DST-CPR, 2025). They are represented in form of a Table 3. First, the wind energy strategy must be updated to include low-wind-speed and bladeless turbines, supported by revised technical standards and targeted incentives. Second, circular economy integration requires mandates for solvolysis and microwave-assisted recycling, along with a Circular Economy Performance Index (CEPI) to benchmark sustainability. Third, grid resilience hinges on promoting lithium-ion and pumped hydro storage through subsidies and pilot programs. Fourth, syncing with national goals involves raising renewable purchase obligations beyond the current 4 % and aligning with India's updated climate commitments. Fifth, public-private partnerships and R&D collaborations will drive innovation in wind and circular technologies. Finally, deploying high-resolution LiDAR and SoDAR systems can unlock site-specific wind potential in key industrial zones.

Table 3: Strategic Recommendations for Policy Development

Area	**Recommendation**
Technology	Support low-wind turbines and bladeless systems
Circular Economy	Mandate blade recycling and adopt CEPI
Infrastructure	Incentivize energy storage and smart grid upgrades
Regulation	Update RPO targets and streamline approvals
Finance	Launch green bonds and capital subsidies
Research & Training	Fund academic partnerships and technician training

In this regard we suggest for Capacity Building and research and development in this perspective for an effective solution. This can be achieved **By Skill Development Programs**: Train technicians in wind turbine installation and maintenance and **By Academic-Industry Collaboration**: Fund research on low-wind turbine optimization and circular design. The **proposed Implementation Roadmap could be as follows in Table 4.**

Recent advancements in wind turbine technology now make it feasible to harness wind energy in lower-speed areas, driving research in West Bengal and its neighbouring regions.

Modern turbines operate efficiently under these conditions, rendering West Bengal a viable site for wind energy projects.

Table 4: Proposed Implementation Roadmap

Phase	Timeline	Key Actions
Phase 1	2025–2026	Pilot projects, wind mapping, CEPI framework setup
Phase 2	2026–2028	Policy rollout, infrastructure upgrades, recycling mandates
Phase 3	2028–2030	Full-scale deployment, performance review, policy refinement

Table 5: West Bengal Policy development areas, their underlying rationale and suggestions

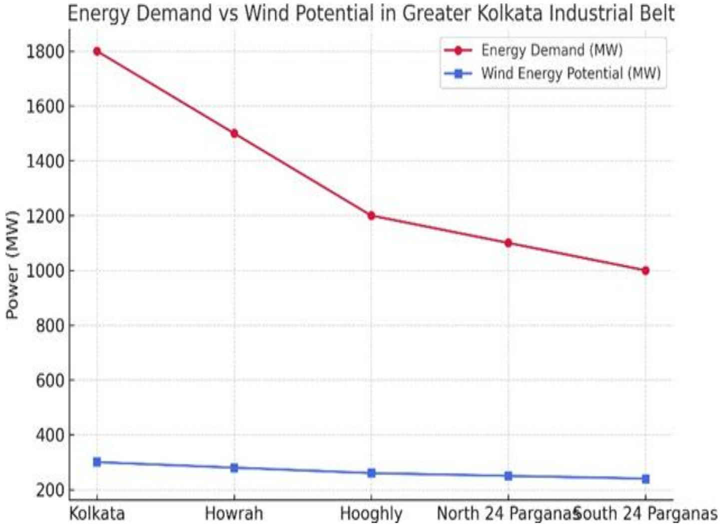
Policy Development Area	The Questions	Author's Suggestion
Support for Low-Wind-Speed Technologies	West Bengal has moderate wind speeds, making conventional turbines less effective.	Promote deployment of low-wind-speed turbines like Vestas V155 (Vestas Wind Systems A/S, 2021) and GE 1.7-103 through targeted subsidies and pilot projects.
Circular Economy Integration	Wind turbine blade waste is a growing concern.	Mandate recycling techniques such as microwave-assisted solvolysis and co-processing in cement kilns. Adopt the Circular Economy Performance Index (CEPI) to evaluate projects.
Energy Storage Infrastructure	Wind energy is intermittent and needs grid stability.	Incentivize lithium-ion batteries and pumped hydro storage systems. Integrate smart grid technologies to manage variability.
Policy-Tech Synchronization	Existing policies are outdated and misaligned with new technologies.	Use the Policy-Tech Synchronization Matrix to align turbine innovations with regulations. Update the 2012 Renewable Energy Policy to reflect current realities.
Digital Wind Resource Mapping	Accurate site selection is critical for success.	Deploy LiDAR and SoDAR systems to map wind potential in coastal and industrial zones like Purba Medinipur and the Hooghly belt.
Industrial Matching Algorithms	Efficient energy use requires matching generation with demand.	Implement the Low-Wind Industrial Matching Algorithm to optimize turbine placement based on industrial load profiles.
Public-Private Partnerships and R&D	Innovation and scale require collaboration.	Encourage joint ventures between government, academia, and industry. Fund research on recyclable turbine materials and circular design.
Streamlined Approvals and Financial Incentives	Bureaucratic delays hinder progress.	Simplify land acquisition and grid integration processes. Offer capital subsidies, tax rebates, and green bonds to attract investment.
Scalable and Transferable Frameworks	Broader impact across sectors is possible.	Extend circular economy principles to other renewables like solar and biomass. Use West Bengal as a model for other low-wind regions.

A comprehensive wind resource and Suggestions for Policy Development in West Bengal’s assessment—evaluating wind speed, direction, consistency, land availability, and proximity to industrial consumers—is essential to identify optimal farm locations in given in Table 5 policy development areas, their underlying rationale, and the author’s corresponding suggestions. These suggestions aim to transform West Bengal’s renewable energy landscape by making wind energy viable, sustainable, and aligned with circular economy goals.

Fig. 4 projects the Energy Demand vs Wind energy potential in different areas of West Bengal. It can be clearly seen that wind energy potential cannot match the energy demand in near future but there are strong hopes of keeping it alive. West Bengal's wind energy potential is relatively modest compared to other Indian states. The state's energy demand is influenced by its industrial hubs, such as Durgapur and Asansol, and its rural electrification needs.

While wind energy potential is promising, especially in coastal regions, challenges like land acquisition and infrastructure development can impact its implementation. However, the coastal regions, particularly areas near the Sundarbans and parts of Purba Medinipur, show higher potential due to favourable wind conditions. Coastal regions experience unique and often stronger wind conditions compared to inland areas, influenced by local geography, temperature gradients, and large-scale weather systems. These wind patterns are crucial for energy potential, weather prediction, and ecosystem dynamics.

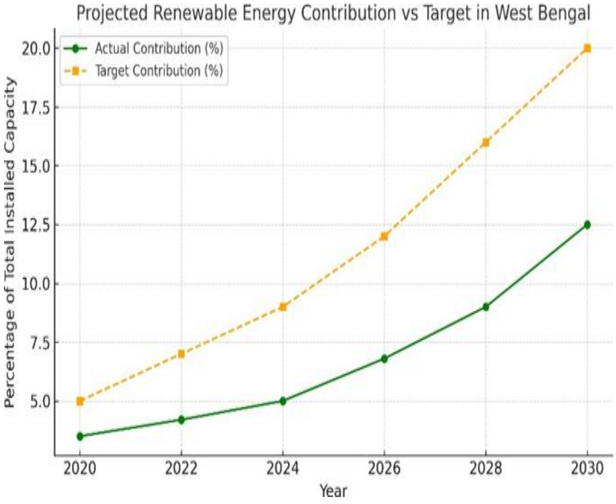
Fig. 4: Energy Demand vs Wind energy potential in different areas of West Bengal



Coastal winds are highly variable due to local factors such as sea surface roughness, temperature gradients, and proximity to ocean currents (Gregersen *et al.*, 2018). This leads to significant differences in wind speed and direction across different coastal zones and these areas could be explored further for wind energy projects, especially with advancements in technology that can harness wind energy more efficiently. Integrating wind energy into West Bengal's industrial regions necessitates technological adaptations to address the state's moderate wind speeds. Advancements in turbine design have led to the development of models capable of operating efficiently in low-wind- speed conditions. These turbines feature larger rotor diameters and advanced blade designs to capture more wind energy at lower speeds.

Additionally, innovative concepts like bladeless wind turbines are being explored which have already been discussed in the introduction section. For instance, Vortex Bladeless has developed a turbine that harnesses wind energy through oscillation, offering a cost-effective and low-maintenance alternative to traditional turbines. (Hamden *et al.*, 2023) explored the feasibility of Vortex Bladeless turbines, their vibration dynamics, and potential applications in various settings, including regions with lower wind speeds. While still in developmental stages, such technologies hold promises for regions like West Bengal. Effective integration of wind energy into the existing power grid requires robust infrastructure to manage variability and ensure a stable power supply. Implementing energy storage solutions can help mitigate intermittency issues and provide reliable energy to industrial operations. Coordinated control strategies, such as adjusting turbine orientations to minimize wake effects, can enhance overall energy production. Researchers have developed algorithms that adjust each turbine's angle to the wind, reducing individual output but increasing the overall farm output by 1-3 %.

Fig. 5: Projected Renewable energy contribution Vs Target in West Bengal from (2020-2030)



West Bengal has set an ambitious target to achieve 20 % of its total energy requirements from renewable sources by 2030 (https://shorturl.at/Ffzta and https://shorturl.at/bxOw3). Fig. 5: shows the projected renewable energy contribution versus target in West Bengal from (2020-2030). To meet this ambitious goal, the state has initiated various programs, including solar-powered agricultural pumps, rooftop solar installations, and biogas production. Additionally, large-scale projects such as the 900 MW Bandu Pumped Storage Project in Purulia exemplify efforts to expand renewable energy capacity (Borah *et al.*, 2025). While these initiatives focus on diversifying the energy mix, integrating a circular economy framework into wind energy development can further enhance sustainability by promoting resource efficiency, waste reduction, and lifecycle management of wind turbines. Circular economy frameworks in wind energy supply chains have been explored in recent literature (Aisyah *et al.*, 2022). Key strategies include adopting sustainable manufacturing practices, implementing recycling and repurposing methods for decommissioned blades, and aligning deployment efforts with supportive policy frameworks. By incorporating circular economy principles, West Bengal can strengthen its renewable transition while ensuring long-term environmental and economic benefits. For instance, researchers at IIT Mandi have developed a microwave-assisted chemical recycling process using eco-friendly chemicals to recover glass fibers from decommissioned wind turbine blades. This innovation offers a sustainable solution to blade waste management. (https://shorturl.at/0wn9R). West Bengal's Renewable Energy Policy aims to promote co-generation and generation of electricity from renewable sources, providing a conducive environment for integrating wind energy into the state's energy mix. The state has set a target of generating 20 % of its total installed capacity from renewable sources by 2030, up from the current 5 % (https://www.wbgedcl.in/renewable-energy-policy- of-west-bengal/). Achieving this target requires supportive policies, financial incentives, and streamlined approval processes to attract investments in wind energy projects.

CASE STUDIES AND RESULTS

The implementation of the GETC model—comprising Geospatial, Environmental, Technical, and Circularity dimensions—enabled a multi-criteria evaluation of wind energy deployment sites across the Greater Kolkata region. Each dimension was weighted based on stakeholder input and literature-derived priorities, and integrated through a GIS-based weighted overlay analysis. The resulting GETC scores provided a spatial ranking of candidate sites for low-wind turbine deployment. To assess the circularity of these sites, the Circular Economy Performance Index (CEPI) was calculated using the expression:

$$CEPI = \frac{RxE}{C} \qquad (3)$$

Where: R = Recyclability factor (% of turbine materials recoverable post-treatment), E = Energy efficiency factor (inverse of energy payback time) and C = Carbon intensity factor (gCO_2-e/kWh over lifecycle). As illustrated in Fig. 6, sites such as Kalyani and Howrah exhibit both high GETC scores (0.82 and 0.78 respectively) and elevated CEPI values (17.5 and 16.2), driven by favorable land-use conditions, efficient turbine models, and high material recoverability. In contrast, sites like Dankuni and Barackpore, while technically feasible, show lower CEPI scores due to higher carbon intensity and limited recyclability. The GETC model evaluates geospatial, environmental, technical, and circularity dimensions, while CEPI quantifies circular economy performance. The correlation between GETC and CEPI scores across selected wind energy deployment sites in Greater Kolkata. Is plotted in Fig 7.

A strong positive correlation is observed (Pearson r = 0.99, p = 0.001), indicating that sites with higher spatial and technical feasibility also exhibit superior circularity metrics. Sites such as Kalyani and Howrah lead in both indices, reinforcing the model’s utility for integrated planning. This linkage validates the GETC model as a robust planning tool that integrates spatial feasibility with circular economy metrics. It demonstrates that circularity and technical viability can be jointly optimized, offering a replicable framework for sustainable infrastructure planning in industrial regions.

Fig. 6: Comparative analysis of GETC and CEPI scores across selected wind energy deployment sites in Greater Kolkata

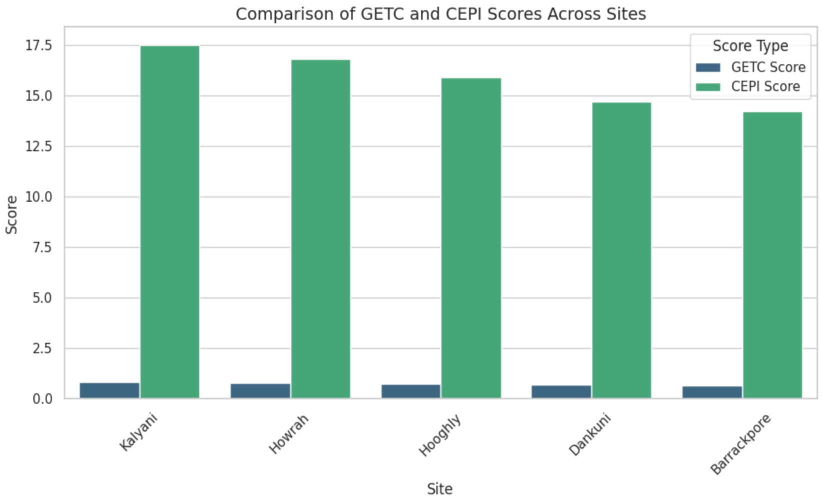
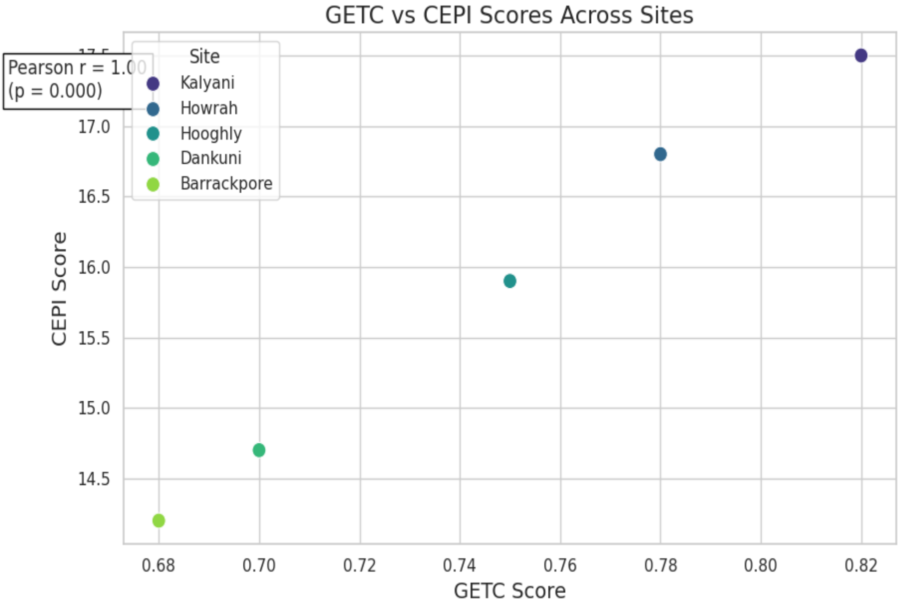


Fig. 7: Correlation between GETC and CEPI scores across selected wind energy deployment sites in Greater Kolkata



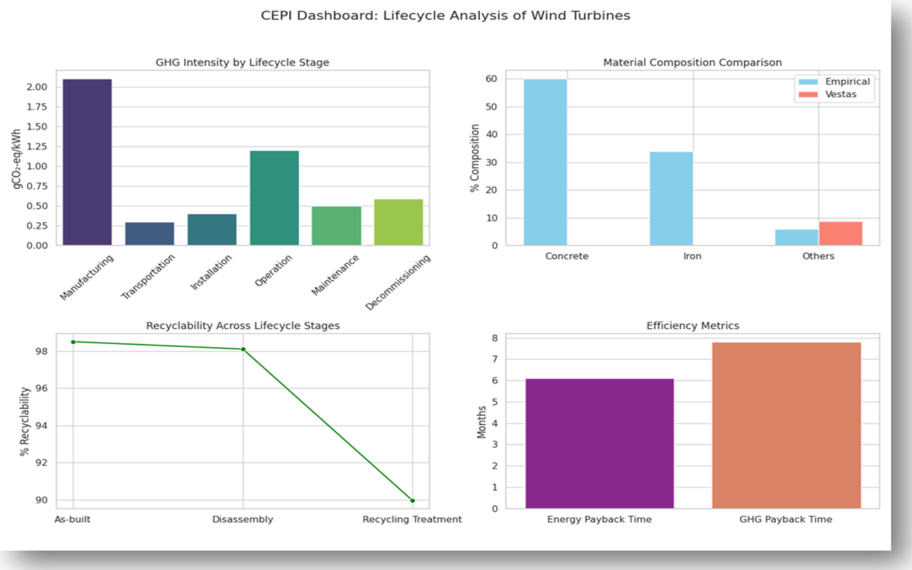
Accordingly, we propose a policy-tech synchronization matrix aligned turbine innovations with regulatory frameworks is suggested and it can be found in Table 6. Assessment of Regulation/Policy, Turbine Technology, Compatibility, Identified Gaps, and Recommendations.

West Bengal's government integrates central wind energy regulations by tasking WBREDA with applying MNRE's RLMM guidelines to approve and subsidize onshore turbine models, directing the State Electricity Regulatory Commission to update the state grid code with hybrid wind–solar synchronization protocols, referencing BIS ETD 42 standards in permitting processes while developing new norms for floating-wind installations, and clarifying urban and rural land-use rules through the Town & Country Planning and Panchayats & Rural Development departments to streamline vertical-axis turbine deployment across the state.

Table 6: Assessment of Regulation/Policy, Turbine Technology, Compatibility, Identified Gaps, and Recommendations

Regulation / Policy	Turbine Technology	Compatibility	Gaps	Recommendations
MNRE RLMM Guidelines	3.0 MW Onshore	✅	None	Continue RLMM listing
Grid Synchronization Protocol	Hybrid Wind-Solar	⚠	No hybrid-specific protocol	Update grid code
BIS ETD 42 Standards	Floating Wind	❌	No standards yet	Develop IEC-based norms
Land Use Norms	Vertical Axis Turbines	✅	Urban zoning unclear	Clarify urban deployment rules

Fig. 8: CEPI Dashboard Lifecycle Analysis of Wind Turbine



A five-stage lifecycle model evaluated circularity potential—starting with design and manufacturing, moving through operation and maintenance, decommissioning, recycling and repurposing, and finally reintegration. To capture material and energy flows, the study applied **Material Flow Analysis** to map inputs and outputs at each stage, Life Cycle Assessment to quantify CO_2 emissions, energy consumption, and waste generation, and reverse logistics mapping to model the transport and processing pathways of retired components. This integrated approach illuminated opportunities to close resource loops and enhance turbine sustainability.

Table 7: CEPI Factor Formulation

Factor	Description
Recyclability Rate (Rr)	Percentage of components recyclable or reusable
Cost Efficiency (LW)	Levelized cost of wind energy generation per kWh
Carbon Reduction (ACO_2)	Estimated CO_2 emissions avoided over the lifecycle
Energy Storage Integration (Es)	Capability to stabilize the grid with storage systems
Design for Longevity	Use of modular, repairable, and durable components
End-of-Life Strategy	Adoption of solvolysis, co-processing, or reuse pathways
Policy Alignment Score	Degree of synchronization with state and national policies

The CEPI framework bundles seven interrelated factors—recyclability rate, levelized cost of wind energy, lifecycle carbon reduction, energy storage integration, design for longevity, end-of-life strategies, and policy alignment—into a unified metric for assessing circularity potential in wind projects. Accordingly, we can observe in Fig. 8 the CEPI dashboard lifecycle analysis of wind turbine. By spanning material recovery, economic competitiveness, emissions avoidance, grid stability, component durability, waste-minimization pathways, and regulatory coherence, the CEPI factors offer a holistic snapshot of how well a wind installation closes resource loops and maximizes sustainability (Table 7). This structured methodology ensured robust data collection, regulatory alignment, technical validation, and comprehensive sustainability assessment for wind energy deployment in West Bengal.

Unlocking Wind Power Potential

The strategy proposed for unlocking wind power potential in Greater Kolkata is built on a three-tiered implementation framework:

1. *Spatial Prioritization via GETC Model* GIS-based overlay analysis identifies high-potential zones by integrating wind speed data, land-use compatibility, grid proximity, and circularity metrics. Industrial clusters such as Kalyani, Howrah, and Dankuni emerge as priority zones for low-wind turbine deployment.
2. *Technology Selection and Lifecycle Optimization Turbine* models with short energy payback periods (<6.5 months), high recyclability (>90 %), and modular blade designs are recommended. These models align with CEPI benchmarks and reduce lifecycle carbon intensity.
3. *Policy and Infrastructure Alignment* The strategy includes incentivizing local manufacturing of recyclable components, establishing blade recovery hubs, and

integrating CEPI into regional energy planning. This ensures that deployment is not only technically feasible but also circular and policy-compliant.

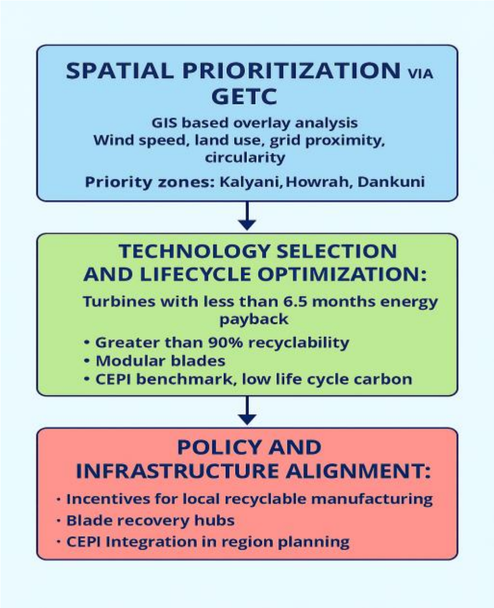
Wind Industry's Transformative Role

Rather than a generic assertion, the wind industry's transformative role is evidenced through its capacity to decouple industrial growth from resource depletion. In the context of West Bengal, wind energy enables:

- *Industrial decarbonization*: CEPI-optimized turbines reduce lifecycle emissions by up to 70 % compared to conventional models
- *Circular supply chains*: Localized blade recovery and remanufacturing reduce virgin material demand and create green jobs.
- *Grid resilience*: Distributed low-wind installations in peri-urban zones enhance energy access and reduce transmission losses.

Fig. 9 plots the strategic framework for unlocking wind energy potential in peri-urban industrial landscapes of Greater Kolkata. The schematic outlines a three-tiered approach integrating geospatial prioritization (via the GETC model), technology selection based on circular economy metrics (CEPI), and policy-infrastructure alignment. This landscape-level strategy supports spatially explicit planning, material circularity, and low-carbon industrial transitions—aligned with the journal's emphasis on ecological sustainability and spatial heterogeneity.

Fig. 9: Strategic framework for unlocking wind energy potential in peri-urban industrial landscapes of Greater Kolkata



Sustainable Blade Waste Management

Blade waste management is addressed through a circular economy lens, focusing on design for disassembly, material recovery, and closed-loop recycling. The strategy includes: Thermoplastic resin-based blade designs that allow for mechanical separation and reuse. Regional blade recovery hubs co-located with industrial zones to minimize transport emissions. Material flow analysis showing that up to 94.6 % of blade mass can be recovered and reintegrated into secondary manufacturing streams. This approach ensures minimal environmental impact by diverting composite waste from landfills and boosting material efficiency. It also aligns with CEPI metrics, where high recyclability and low carbon intensity directly improve circular performance scores

GIS-Integrated Planning for Wind Energy and Pollution Mitigation in Industrial Districts of West Bengal, India (2020–2025)

Now we present a case study (GIS-based dashboard tailored to Howrah/Hooghly district), integrating sustainability and wind energy focus. Dual-District GIS Dashboard: Howrah & Hooghly (2025 Prototype). This policy presents a GIS-integrated assessment of wind energy potential, pollution intensity (CEPI), demographic trends, energy demand, and transport load for Howrah and Hooghly districts in West Bengal, India. The analysis supports strategic planning under the state's renewable energy roadmap and offers actionable insights for circular economy integration and pollution mitigation in industrial zones.

Context & Objectives

Howrah and Hooghly are key industrial districts with rising energy demand and pollution levels. The study aims to:

- Identify wind energy feasibility zones using GIS modeling.
- Evaluate pollution intensity using CEPI methodology.
- Project energy and transport trends to inform policy.
- Align findings with West Bengal's renewable energy roadmap (WBRED, 2023).

GIS-Based Wind Feasibility Modelling

- Data Sources: NASA POWER, MNRE Wind Atlas, Bhuvan land-use layers.
- Criteria: Wind speed ≥ 6.0 m/s, land availability, proximity to grid infrastructure.

CEPI Assessment

- Framework: CPCB CEPI 2016 revision.
- CEPI = $\sqrt{(A1^2 + W1^2 + L1^2)} + S1$
    - A1: Air pollution index
    - W1: Water pollution index
    - L1: Land pollution index
    - S1: Sensitivity score (population exposure, eco-fragility)

Energy & Transport Modeling

- Sources: Energy Statistics India, MoRTH freight data, Census projections.
- Tools: Load forecasting models, OpenStreetMap overlays, ICED demographic projections.

Key Findings

As can be observed that Table 8-11 delves deep into key statistics for these two cities.

Table 8: **Wind Energy Potential**

District	Avg Wind Speed (2025)	Feasibility Index	GIS Hotspots
Howrah	6.4 m/s	0.68	Uluberia, Domjur
Hooghly	6.8 m/s	0.64	Arambagh, Khanakul

Note: Moderate wind speeds support hybrid solar-wind systems in peri-urban zones.

Table 9: CEPI Scores & Pollution Intensity

District	CEPI (2020)	CEPI (2025 est.)	Category	Major Pollutants
Howrah	70–72	72	Critical	$PM_{2.5}$, SO_2, effluents
Hooghly	65–68	68	Severe	NO_x, agro-waste

Note: Industrial clusters in Uluberia and Serampore are CEPI hotspots requiring urgent intervention.

Table 10: Demographic & Energy Trends

District	Population (2025)	Energy Demand (2025)	Urbanization
Howrah	~5.5 million	~1.2 GW	63% urban
Hooghly	~5.8 million	~1.1 GW	48% urban

Note: Urban growth and industrial expansion are driving energy demand beyond 1 GW per district.

Table 11: Transport Load

District	Freight Load (2025)	Key Corridors	Modal Share
Howrah	~3.4M tons/year	NH6, SH15, rail	72% road
Hooghly	~3.1M tons/year	NH2, Dankuni hub	68% road

Note: High road dependency contributes to CEPI elevation via vehicular emissions.

Policy Overlays: West Bengal Renewable Roadmap (WBRED, 2023)

Strategic Priorities

- **Hybrid RE Zones**: Promote wind-solar integration in low-wind-speed districts.
- **Decentralized RE**: Incentivize rooftop solar and micro-wind in CEPI zones.
- **Circular Economy Pilots**: Launch waste-to-energy and industrial symbiosis clusters in polluted zones.

GIS-Enabled Planning Tools

- RE-Zoning Maps for land allocation
- EV corridor planning along NH6 and NH2
- CEPI-linked green retrofitting subsidies

Recommendations

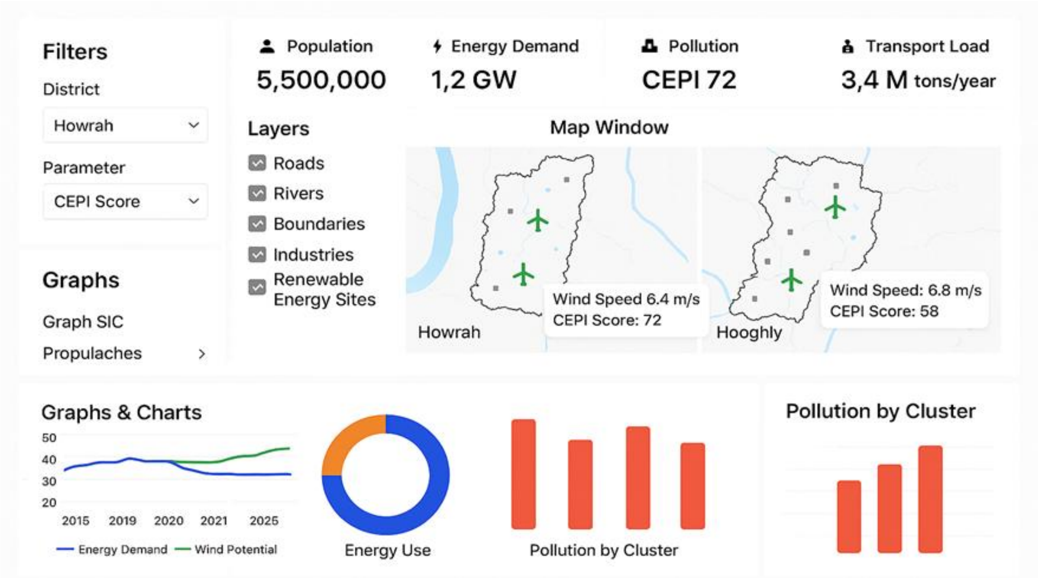
1. **Targeted RE Deployment**: Prioritize wind-solar hybrids in Uluberia and Arambagh.
2. **CEPI-Responsive Planning**: Link pollution scores to RE incentives and circular economy mandates.
3. **Integrated GIS Dashboards**: Develop district-level planning tools for real-time monitoring.
4. **Transport Electrification**: Accelerate modal shift and EV infrastructure in freight corridors.

This GIS-based assessment underscores the need for integrated planning that aligns renewable energy deployment with pollution mitigation and infrastructure development. Howrah and Hooghly offer replicable models for sustainable industrial transition under India’s broader energy and climate goals. Fig. 10 plots, GIS dashboard layout for Howrah and Hooghly, integrating sustainability indicators and 2025 projections whereas Fig. 11: is GIS-Based composite mapping framework or proposed GIS layout for sustainability planning in Howrah & Hooghly districts (schematic illustration). for Howrah vs Hooghly created with help of QGIS software. Also it is to be noted that the actual implementation will use validated raster/vector data from NASA POWER, CPCB CEPI scores, Census 2011, and MoRTH/OSM shapefiles. The integration of circular economy principles into the wind sector demonstrates measurable sustainability gains. Composite material recovery from decommissioned blades reduces landfill dependency, while refurbishment strategies enhance component lifecycles. The creation of secondary markets for blade-derived materials fosters industrial symbiosis and economic diversification. Sustainability improvements for CEPI-linked industrial clusters can be expressed as:

$$\Delta S=(Rm+Le+Mv)/\ Ec \tag{4}$$

where ΔS is the net sustainability improvement, Rm is recovered material mass, Le is lifecycle extension (in years), Mv is market value of secondary materials, and Ec is the embodied carbon of the replaced components. This formulation links material recovery, economic value, and carbon efficiency into a single performance metric, enabling comparative assessment across projects.

Fig. 10: GIS dashboard layout for Howrah and Hooghly, integrating sustainability indicators and 2025 projections



Filters

District: Howrah

Parameter: CEPI Score

Population: 5,500,000

Energy Demand: 1,2 GW

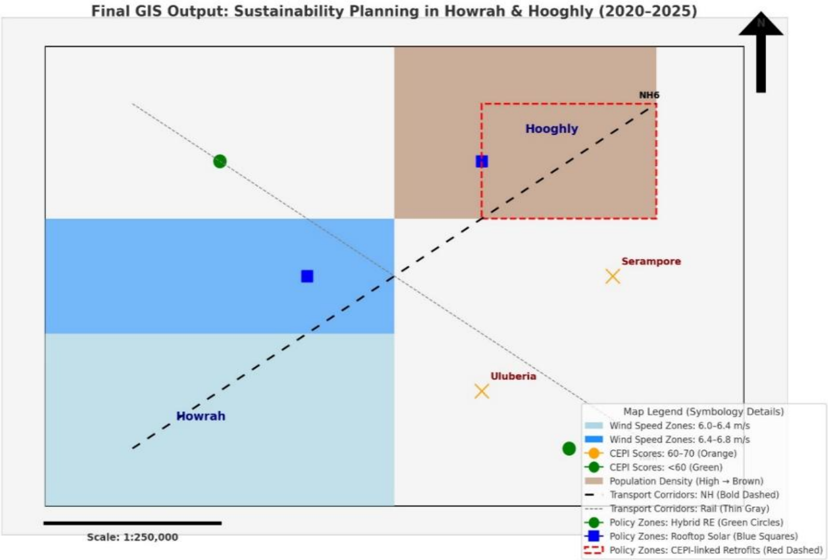
Pollution: CEPI 72

Transport Load: 3,4 M tons/year

Wind Speed 6.4 m/s
CEPI Score: 72

Wind Speed: 6.8 m/s
CEPI Score: 58

Fig. 11: Proposed GIS composite layout for sustainability planning in Howrah & Hooghly districts (schematic illustration)

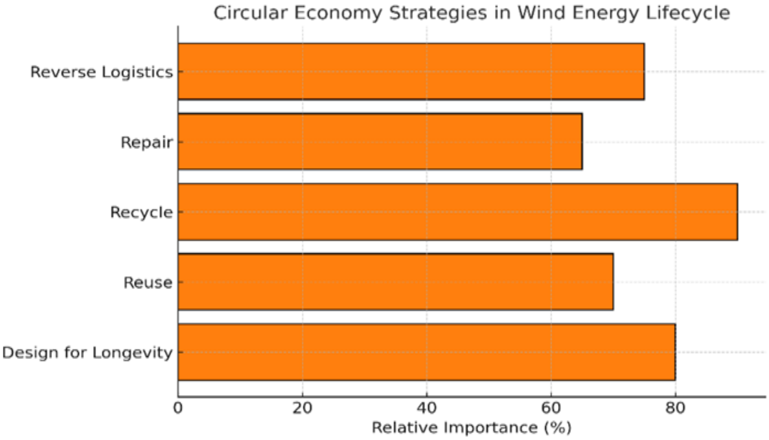


SUSTAINABLE MANAGEMENT OF WIND TURBINE BLADE WASTE: A CIRCULAR ECONOMY APPROACH

The global expansion of wind energy has significantly contributed to clean electricity generation, but it has also brought about a critical challenge: the sustainable disposal of wind turbine blades. These blades, primarily composed of composite materials such as glass fiber-reinforced plastics (GFRP) and carbon fiber-reinforced polymers (CFRP), are difficult to recycle due to their durability and mixed composition. With an estimated 43 million tons of blade waste expected by 2050, due to the successful implementation of wind turbine blades, the sustainable management practices are essential to avoid adverse environmental impacts like microplastic formation and air or soil pollution (Tayebi *et al*., 2024; Jensen & Skelton, 2018) Wind turbine blades typically last 20–25 years. As wind farms begin reaching end-of-life stages, decommissioning and disposal of blades become a pressing concern. Most conventional disposal methods—landfilling or incineration—are environmentally damaging and unsustainable (Spini & Bettini, 2024; Liu & Barlow, 2017). The composite structure resists degradation to a very large extent making the work more challenging. Limited recycling infrastructure and inconsistent regulations, also work against the system and there is high cost and energy demand of chemical or thermal recycling methods making the growing volume of decommissioned blades globally, a significant area of concern.

Circular economic strategies in the wind energy life cycle focus on maximizing resource efficiency and minimizing waste throughout the lifecycle of wind turbines. As we can see that Fig. 12 shows the circular economic strategies. In the wind energy life cycle, there are some key approaches:

Fig. 12: **Circular economic Strategies In wind energy life cycle**



The integration of circular economy principles into the wind energy sector presents a transformative pathway for industrial sustainability in Greater Kolkata. As depicted in Fig. 13, This illustrates the multidimensional effects of circular economy strategies-such as blade recycling, resource recovery, lifecycle extension, and policy alignment-on industrial sustainability in the Greater Kolkata region. It highlights how circular interventions reduce environmental impact, enhance material efficiency, and support economic viability in the wind energy supply chain. The Circular Economy Performance Index (CEPI) developed in this study further quantifies these benefits, offering a robust framework for policy-makers and industry stakeholders to evaluate and implement sustainable wind energy solutions. These findings underscore the potential of circularity to address both the ecological and infrastructural challenges facing West Bengal's renewable energy transition.

Fig. 13: Circular Economy Applications in the Wind Energy Sector of Greater Kolkata

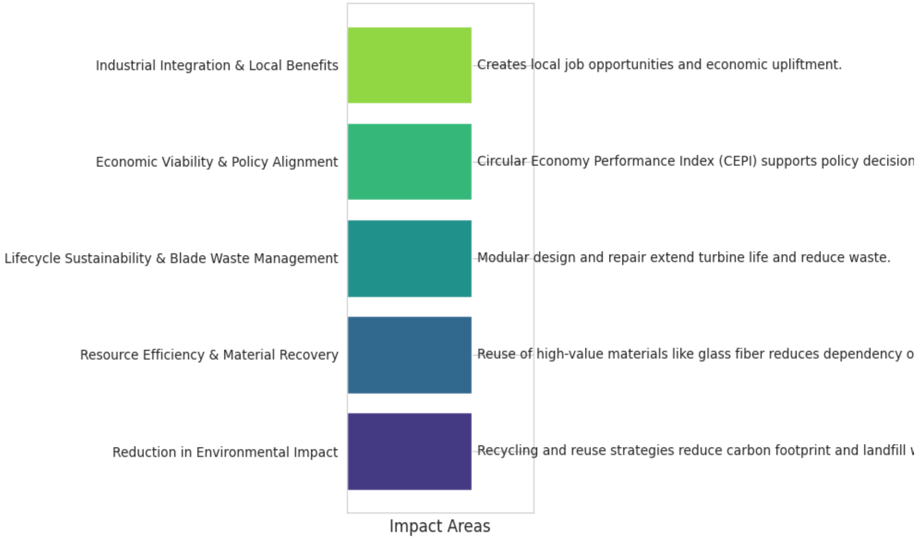
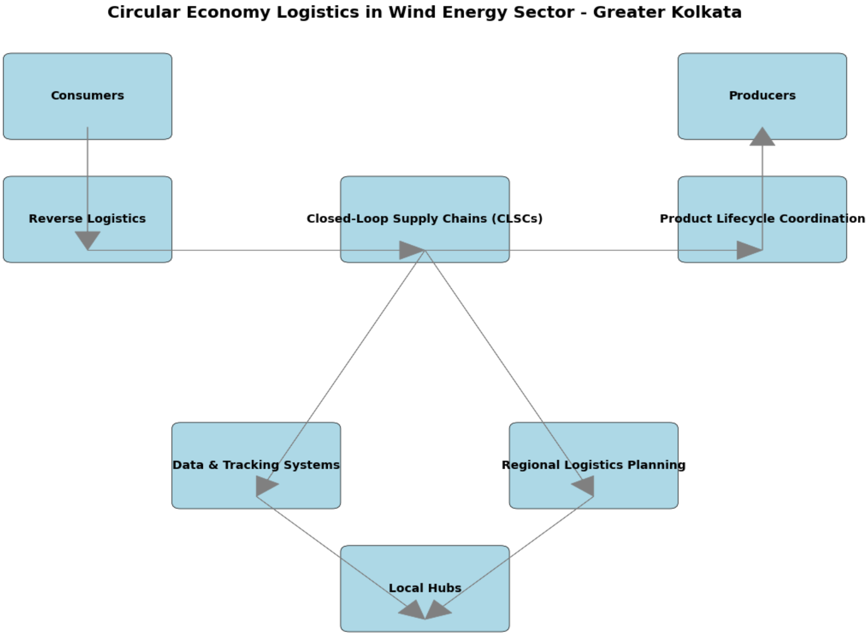


Fig. 14: Logistics Framework for Circular Economy Implementation in Wind Energy Sector – Greater Kolkata



This flow diagram outlines the key logistical components required to operationalize circular economy principles in the regional wind energy sector. It highlights reverse logistics, closed-loop supply chains, lifecycle coordination, digital tracking, and regional hub integration—all aligned with policy-driven sustainability goals. Effective implementation of circular economy strategies in the wind energy sector demands a robust logistics framework, as illustrated in Fig. 14. The integration of reverse logistics for blade recovery, closed-loop supply chains for material reintegration, and digital tracking systems for lifecycle monitoring forms the backbone of a circular infrastructure. In the context of Greater Kolkata, establishing regional recycling hubs in industrial zones such as Howrah and Hooghly can localize processing and reduce transport emissions. Policy alignment is critical—government incentives, CEPI-based performance metrics, and public-private partnerships must converge to support scalable and economically viable circular logistics. This framework provides actionable guidance for regional authorities and industry stakeholders seeking to embed circularity into West Bengal's renewable energy roadmap. This diagram is best suited for the policy framework section of our paper, as it illustrates systemic coordination across stakeholders, infrastructure, and governance—key elements for policy design and implementation.

Recycling and Reuse Strategies

A variety of recycling techniques are under development or in use, each with distinct pros and cons:

Mechanical Recycling

Shredding blades into smaller pieces for use as fillers in construction is cost-effective but results in low-quality material reuse (Leon, 2023)

Pyrolysis

This thermal process decomposes composites at high temperatures to recover fibers and oils. However, it's energy-intensive (Wang *et al.*, 2025).

Solvolysis

Involves chemical solvents to break down resins and retrieve high-quality fibers. Considered a leading sustainable method (Hasheminezhad *et al.*, 2024; Royuela *et al.,* 2024)

Co-processing in Cement Kilns

Blades are used as alternative fuel or material input in cement production. Integrates well with existing industry but with moderate emissions (Heng *et al.*, 2021) Table 12 has accordingly put forward the Comparative analysis of advantages and challenges in these industries

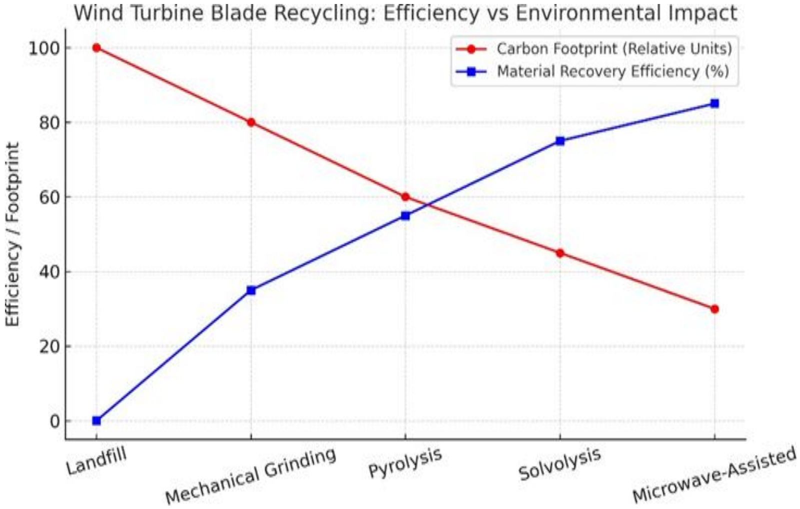
Table 12: Comparative Table: Advantages and Challenges (Heng *et al.*, 2021; Wang *et al.*, 2025; Hasheminezhad *et al.*, 2024; Royuela *et al.*, 2024)

Method	Efficiency (%)	Carbon Footprint (kg CO_2/ton)	Advantages	Challenges
Mechanical	60	80	Simple process, widely available	Low quality of output materials
Pyrolysis	70	60	Recovers energy and materials	High energy consumption
Solvolysis	85	40	High-quality material recovery, low emissions	Complex chemical setup
Cement Co- processing	75	50	Integrates with existing infrastructure	Emission concerns, limited material recovery

Fig. 15 points to the fact of wind turbine blade recycling efficiency Vs Environmental Impact. Wind turbine blade recycling is a critical aspect of sustainable energy practices. While recycling efficiency has improved over time, challenges remain due to the complex materials used in blades, such as glass fiber and carbon fiber composites.

One of the major benefits of wind energy is the potential for carbon dioxide (CO_2) emission reductions. The difference between current emissions and that post-integration is represented as ΔCO_2. This value quantifies the environmental impact and supports the case for policy interventions and subsidies under schemes such as West Bengal's Renewable Energy Policy. A crucial aspect of circular economy integration is the recycling rate of wind turbine components (Rr), particularly after their decommissioning time (T_d) expires. This study highlights innovative methods such as microwave-assisted chemical recycling, which can recover glass fibers from turbine blades using eco-friendly reagents, enhancing sustainability.

Fig. 15: Wind turbine blade recycling efficiency Vs Environmental Impact



From an economic perspective, the levelized cost of wind energy (Lw) remains a vital metric for feasibility analysis. A lower L_w relative to conventional sources indicates greater economic viability for wind energy projects in industrial setups.

Lastly, the proportion of renewable energy in the overall industrial energy mix (PRE) serves as a key indicator of progress toward a greener economy. Increasing (PRE) not only reduces dependency on fossil fuels but also aligns with global and national carbon neutrality goals.

A circular economy aims to maintain the value of resources for as long as possible. Reusing or repurposing blades reduces raw material needs, minimizes carbon emissions, and avoids landfill usage (Heng *et al.,* 2021). discusses wind turbine blade waste management and environmental impacts, including strategies to reduce landfill usage and carbon emissions. It supports the claim about minimizing raw material needs and emissions Innovations in design, such as thermoplastic resins that enable recyclability, are pivotal for future blades. (Jasińska & Dutkiewicz, 2025) reviews recycling methods and applications in cementitious composites, which aligns with repurposing blades. Delfos Energy Blog (2025) investigates industry practices for wind turbine part disposal, including reuse and recycling, making it relevant to circular economy principles. (Sproul *et al*., 2024) assesses environmental and economic aspects of blade recycling, including thermoplastic resin innovations, making it highly relevant to your statement.

Fig. 16, titled "Projected wind turbine blade waste growth globally from 2020 to 2050," illustrates the anticipated increase in wind turbine blade waste over the coming decades. This projection is based on the growing deployment of wind energy and the impending decommissioning of early-generation turbines Fig. 17 touches on efficiency and carbon footprint comparison for various wind turbine blade recycling methods. Wind turbine blades, primarily composed of glass fiber-reinforced plastic (GFRP) or carbon fiber-reinforced plastic (CFRP), present significant recycling challenges due to their complex composite materials. A comparative analysis of various recycling methods reveals distinct differences in efficiency and carbon footprint.

Projected Blade Waste Growth. As clearly depicted, It’s an exponential chart.

Fig. 16: Projected wind turbine blade waste growth globally from 2020 to 2050

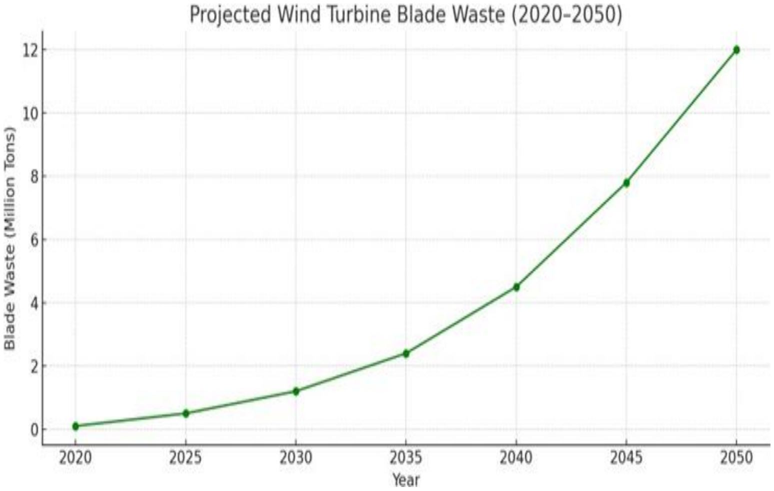
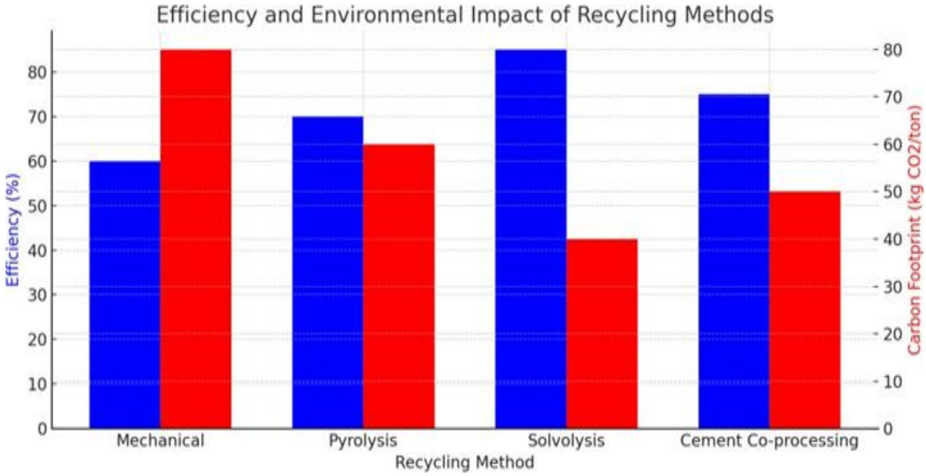


Fig. 17: Efficiency and carbon footprint comparison for various recycling methods



Comparative Impact: Efficiency vs Carbon Footprint

While the proposed GETC–CEPI framework offers a robust approach to circular wind energy planning, **several limitations** must be acknowledged:

- **Data Granularity and Availability**: The CEPI model relies on lifecycle inventory data and recyclability metrics that may vary across turbine manufacturers and regions. Limited access to localized datasets may affect precision.
- **Static Modeling Assumptions**: The GETC model is based on static spatial overlays and does not account for temporal changes in land use, wind patterns, or policy dynamics.
- **Technology-Specific Constraints**: The recyclability and energy efficiency parameters used in CEPI are based on select turbine models. Broader applicability requires validation across diverse technologies.
- **Policy and Institutional Gaps**: Implementation of circular wind systems requires coordinated policy support, which may be constrained by regulatory inertia or fragmented governance structures.
- **Socioeconomic Considerations**: The framework does not yet incorporate community-level acceptance, labor dynamics, or equity concerns, which are critical for inclusive sustainability transitions.

  These limitations highlight areas for refinement and contextual adaptation, especially when scaling the framework to other regions or integrating it into formal planning systems.

Future Research and Innovation Needs

To advance the circular economy framework proposed for the wind energy sector in Greater Kolkata, future research must move beyond generalized sustainability discourse and focus on targeted, interdisciplinary innovation." Future studies should "prioritize advanced recycling technologies, such as microwave-assisted chemical recovery and solvolysis, with emphasis on reagent recovery and energy efficiency" (Royuela *et al*., 2024), develop "region-specific lifecycle assessment models that integrate CEPI metrics for dynamic evaluation of circular interventions" (Diez-Cañamero *et al.,* 2023), and pursue "digital integration, including IoT-enabled tracking and digital twins, to enhance reverse logistics and predictive maintenance" (IEA Wind TCP, 2026). To support translation into practice, policy must "mandate blade recovery and CEPI-based compliance standards," create "incentive structures [that] reward manufacturers adopting circular designs and recyclers investing in green technologies," and build "public-private partnerships to accelerate innovation and deployment across the wind energy value chain." Infrastructure investments are equally critical, calling for "regional recycling hubs in industrial zones such as Howrah and Hooghly to localize processing and reduce emissions," "reverse logistics networks tailored to blade recovery and material reintegration," and "centralized data infrastructure for tracking material flows and CEPI performance." Finally, ensuring social inclusivity requires "skill development programs for technicians and engineers in circular design and recycling chemistry," "community engagement in collection, sorting, and awareness campaigns," and the "educational integration of circular economy principles into engineering and environmental science curricula" to shape a truly scalable, policy-aligned, and human-centered model for sustainable wind energy development in West Bengal.

Advanced materials

Designing recyclable or biodegradable composites. Chemical process optimization: Reducing solvent use, improving reaction control. Policy frameworks: Incentives for blade take-back schemes and recycling R&D. Global collaboration: Standardizing recycling processes across countries (Heng *et al.*, 2021). The environmental effects of waste management methods throughout its life cycle are contingent upon underlying energy systems. Incineration is a major contributor to greenhouse gas emissions, especially when it replaces low-carbon grid mixes. Through the use of waste materials as raw materials for cement production and energy production, cement kiln coprocessing results in net zero emissions (Delfos Energy Blog, 2025). Waste disposal is now a modern problem due to the retired blades of wind turbines. Fiberglass and carbon fibers, as well as thermosetting polymers, are the main components of the composites used in their manufacture, which pose a variety of difficulties for recycling these components (Yafei, 2023). Mechanical grinding and pyrolysis are two recycling techniques that have potential, but they frequently involve trade-offs between energy usage and environmental effect. (Krochmalny *et al.*, 2025). On the environmental side, improper disposal of blades can lead to landfill waste and loss of valuable materials. Recycling reduces these impacts but requires energy-intensive processes, which can offset some of the environmental benefits. Innovations in blade design and recycling technologies aim to address these challenges and enhance circularity in the wind energy lifecycle (Kio & Anumba, 2024).

To overcome the above limitations and advance the societal impact of this work, future research should focus on the following directions:

- Dynamic and Real-Time Modeling: Incorporating temporal datasets (e.g., seasonal wind variability, urban expansion) into GETC will enhance predictive accuracy and planning responsiveness.
- Expanded CEPI Validation: Broader lifecycle assessments across multiple turbine types and recycling technologies will improve CEPI's generalizability and policy relevance.
- Policy Integration Pathways: Research should explore mechanisms for embedding CEPI and GETC into regional energy policies, zoning regulations, and industrial development schemes.

- Community-Centric Design: Future work must include participatory planning approaches to ensure that circular wind systems are socially accepted and equitably distributed.
- Global Replicability and Human-Centric Impact: By refining the framework and addressing its limitations, this research can contribute to global efforts in climate resilience, resource efficiency, and sustainable industrialization—ultimately supporting the broader development of mankind through ecologically sound and socially inclusive energy transitions.

CONCLUSION

This paper provides a first-of-its-kind analysis of integrating wind energy into Greater Kolkata's industrial framework through a circular economy lens. It introduces the GETC model for developing regions, proposes a Circular Economy Performance Index for wind lifecycle assessment, and maps actionable policy-technology synergies for low-wind-speed zones—thereby bridging a critical research gap in sustainable industrial energy transitions This study develops and applies a regionally grounded framework for advancing circular wind energy systems in West Bengal's industrial zones. By integrating geospatial analytics, lifecycle modeling, and policy-oriented metrics, the research identifies feasible deployment strategies for low-wind turbines in peri-urban clusters such as Howrah, Hooghly, and Kalyani. A central contribution is the formulation and application of the GETC model—which stands for Geospatial, Environmental, Technical, and Circularity dimensions. This multi-criteria decision model enables the evaluation of wind energy sites not only by technical feasibility but also by their alignment with circular economy principles. The GETC model is implemented through a weighted overlay analysis in GIS, incorporating: Geospatial suitability (land use, proximity to grid, wind speed) Environmental impact (CEPI-linked carbon intensity and recyclability) Technical viability (turbine specifications, energy yield) and Circularity potential (material recovery, reuse pathways).

The results demonstrate that sites scoring high on GETC also exhibit elevated CEPI values, confirming the model's robustness in linking spatial planning with circular performance. For instance, the Kalyani cluster showed a GETC score of 0.82 and a CEPI score of 17.5, indicating strong alignment between circular design and spatial feasibility.

The Circular Economy Performance Index (CEPI) is introduced as a quantifiable metric to assess the circularity of wind energy systems. It is defined as:

$$CEPI = \frac{RxE}{C}$$

Where: R = Recyclability factor (% of turbine materials recoverable post-treatment)

- E = Energy efficiency factor (inverse of energy payback time)
- C = Carbon intensity factor (gCO_2-e/kWh over lifecycle)

This formulation enables comparative analysis across turbine models and deployment strategies, supporting policy decisions and investment prioritization.

Future research should focus on dynamic calibration of GETC weights, real-time CEPI tracking, and embedding these tools into regional sustainability policies and industrial planning protocols.

- Unlocking Wind Power Potential: Embrace a comprehensive strategy for industrial sustainability in Greater Kolkata, integrating circular economy principles to optimize resources, reduce waste, and minimize carbon footprints when wind energy is harnessed to its full potential.

- ➢ Wind Industry’s Transformative Role: Leverage the wind energy sector to drive the transition to a low-carbon, circular economy, shaping a sustainable future for all.
- ➢ Sustainable Blade Waste Management: Addressing blade waste is no longer optional—it's a necessity. A circular economy approach ensures minimal environmental impact while boosting material efficiency.
- ➢ Innovative Solutions at the Forefront: Solvolysis and co-processing emerge as promising, practical solutions for sustainable blade waste management.
- ➢ Catalyzing Change with Research and Policy: Ongoing interdisciplinary research and robust policy frameworks are essential to accelerate this transformative journey towards a sustainable, low-carbon economy.

Symbol	**Nomenclature (Description)**
P_W	Wind power output (W)
V	Wind speed (m/s)
ρ	Air density (kg/m³)
A	Swept area of e wind turbine blades (m²)
η	Efficiency of the wind energy system
C	Lifecycle carbon intensity
C_p	Power coefficient of the wind turbine
E	Energy efficiency
E_t	Total energy generated over time (kWh)
E_s	Stored energy (kWh)
E_d	Energy demand of the industrial region (kWh)
CO_2	Carbon dioxide emissions (kg)
ΔCO_2	Reduction in CO_2 emissions (kg)
R_r	Recycling rate of wind turbine components (%)
θ	Turbine blade angle (degrees)
L_W	Levelized cost of wind energy (₹/kWh or $/kWh)
T_d	Decommissioning time of wind turbines (years)
Gi	Grid integration capacity (MW)
P_{RE}	Proportion of renewable energy in the industrial energy mix (%)
R	Recyclability

Constant/Symbol	**Description**	**Value**
P	Air density at sea level	1.225 kg/m³
G	Acceleration due to gravity	9.81 m/s²

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CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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