Indian Institute of Technology Bombay

Repowering of Wind Power Plants:

A Feasibility Study

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Disclaimer

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Note: *This report, prepared for Maharashtra Energy Development Agency (MEDA), is a confidential document*

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List of Abbreviations

CUF	Capacity Utilization Factors
CEA	Central Electricity Authority
DISCOMS	Distribution Company
ESZ	Ecologically Sensitive Zone
EIA	Environmental Impact Assessment
ESS	Energy Storage System
IRR	Internal Rate of Return
LCOE	Levelized Cost of Electricity
MNRE	Ministry of New and Renewable Energy
MoEFCC	Ministry of Environment, Forest, and Climate Change
MSEDCL	Maharashtra State Electricity Distribution Company Limited
NBWL	National Board for Wildlife
NIWE	National Institute of Wind Energy
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
PARIVESH	Pro-Active and Responsive facilitation by Interactive, Virtuous, and Environmental Single-window Hub
PPA	Power Purchase Agreement
PV	Photovoltaic
PPP	Public-Private Partnerships
RE	Renewable Energy
SIA	Social Impact Assessment
TPC	Total Project Cost
VGF	Viability Gap Funding
WTG	Wind Turbine Generators

Executive Summary

Wind power plant (WPP) owners nearing the end of turbine operational lifespans: need to make acritical decision, extend existing wind turbine generator life, decommission, or repower. Repowering has emerged as a transformative strategy to boost renewable energy (RE) generation while addressing the challenges posed by aging wind turbines. This report examines the feasibility, challenges, and opportunities of repowering existing wind farms in Maharashtra, with a special focus on the Chalkewadi wind farm in Satara District.

Maharashtra, a leader in wind energy development since 1986, has leveraged its wind-rich sites for three decades. However, many early installations feature low-capacity turbines with modest hub heights and suboptimal capacity utilization factors (CUF), despite the strong wind resources in these locations. Technological advancements now enable the replacement of outdated turbines with modern, high-capacity models, significantly improving CUF and unlocking the full potential of these wind-rich sites.

This report explores the potential of repowering wind power projects, with a focus on optimizing land use, increasing energy output, and aligning with evolving policy and financial dynamics. It examines key challenges such as decommissioning complexities, logistical constraints, micro-siting arrangements, and environmental considerations, while highlighting benefits like improved energy yield, operational efficiency, and CUF. The regulatory framework is reviewed through an analysis of eligibility criteria and relevant policies, offering guidance for streamlined implementation in compliance with industry standards and regulations. The report emphasizes the importance of infrastructure upgrades, power evacuation planning, and compliance with environmental and regulatory requirements. Particular attention is given to sensitive ecosystems in the Western Ghats and the need for clearances related to wildlife and forest areas.

The report also conducted a case study in Chalkewadi site using an optimization algorithm developed based on the constraints outlined in the Ministry of New and Renewable Energy (MNRE) guidelines for repowering. The algorithm focuses on maximizing energy output. A case study offers insights into the feasibility of wind repowering for both standalone and hybrid

scenarios. The findings underscore the technical, economic, and environmental advantages of repowering, while also addressing key constraints and risks.

Despite the technical and environmental benefits, significant challenges hinder widespread adoption of repowering projects. These include complexities in multi-owner wind farm sites, continuation of existing power purchase agreements (PPAs), regulatory hurdles, and the need for substantial investment in power evacuation infrastructure. The report underscores that without targeted policy support, financial incentives, and regulatory reforms, developers are unlikely to independently pursue repowering initiatives.

The report concludes with actionable recommendations, including policy enhancements, financial incentives, and stakeholder collaboration to accelerate the adoption of repowering projects in Maharashtra. This comprehensive assessment provides a roadmap to modernize wind energy infrastructure, contributing to India’s renewable energy goals and its transition to a sustainable energy future.

1 Introduction

The global energy landscape is undergoing a profound transformation as the countries across the world respond to the pressing need to combat climate change, ensure energy security, and reduce dependence on finite fossil fuel resources. Conventional energy sources like coal, oil, and natural gas are major contributors to greenhouse gas emissions, resulting in severe environmental degradation. With the rising costs of environmental inaction, RE sources have become central to sustainable development goals, offering a pathway to cleaner, more resilient energy systems. Among RE technologies, wind energy has been a pivotal player. Wind power harnesses natural wind resources to generate electricity without producing direct carbon emissions, providing a scalable, sustainable, and economically viable alternative to fossil fuels. As a mature technology with significant commercial potential, wind energy has grown rapidly over the past few decades.

According to the International Energy Agency (IEA), the energy sector is experiencing a significant shift globally, with renewables increasingly dominating the power mix. From 2023 to 2028, nearly 3,700 GW of new RE capacity is being added to the energy sector, surpassing the total capacity installed over the past century (IAE 2024). Key milestones include wind and solar photovoltaic (PV) generating more electricity than hydropower by 2024, renewables surpassing coal by 2025, and wind and solar PV together accounting for 25% of global electricity by 2028. This growth highlights the rapid shift toward a cleaner, more sustainable energy future. The IEA reports that global wind capacity has reached unprecedented levels, with wind energy accounting for a substantial share of the RE mix in many countries. For instance, Denmark's power mix is heavily influenced by wind energy, which contributed over 57% of the country's electricity generation in 2023 (IRENA 2024). However, the transition to wind energy is not without challenges, as the intermittent nature of wind and site-specific limitations affecting its reliable integration into conventional power grids.

As reported by the Central Electricity Authority (CEA), the projected installed capacity of various RE sources in India demonstrated a substantial increase, reinforcing the country’s commitment to increasing its share of clean energy. As of August 2024, India’s installed RE capacity stands at

152.65 GW, accounting for more than 34% of the country's total power capacity (See Figure 1). India has been harnessing wind energy for over 40 years. As of September 2024, the country boasts a total installed wind power capacity of 47.36 GW, securing its position as the 4th largest globally.

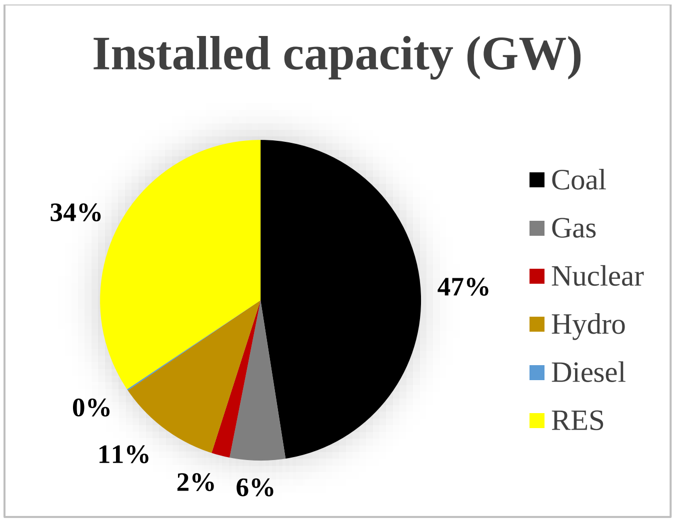

Figure 1: Installed capacity source wise *(CEA Dashboard 2024)*

In alignment with global climate goals, India has committed to expanding its RE capacity. At COP26, India announced ambitious targets for the country, aiming for 50% of installed power capacity to come from non-fossil sources by 2030. Although the country set a 60 GW target for wind energy by 2022, only 41.9 GW was achieved by the end of that year, reflecting challenges in accelerating wind capacity additions. India's updated Nationally Determined Contributions (NDC) under the Paris Agreement reaffirm its commitment, highlighting wind energy as critical to meeting these targets.

India's wind sector faces significant challenges, including limited high-quality wind sites, land acquisition hurdles, and a reliance on outdated, less efficient turbines, particularly in wind-rich states like Tamil Nadu, Maharashtra, and Gujarat. Many of the country's prime wind sites (Class-I/II) are already occupied by low-capacity old turbines with low-CUF, which limits their effectiveness in supporting India's RE goals. Aging wind farms also experience declining energy output and rising maintenance costs due to worn-out equipment, inadequate maintenance, and outdated technology.

In response, the MNRE introduced a Policy for Repowering of the Wind Power Projects in 2023, targeting 25.4 GW of repowering potential. This policy aims to replace smaller, aging turbines with fewer, high-capacity, and more efficient models, optimizing the use of limited high-potential sites. Repowering offers an effective solution to maximize the generation potential of existing installations, enhancing energy output while optimizing land use. By upgrading existing infrastructure and equipment, repowering helps ensure that wind and solar farms remain efficient and productive, supporting India's clean energy transition.

1.1 Literature Review

(Martínez, et al. 2018) explored the life cycle model for repowering low-capacity wind turbines, examining both the advantages and environmental impacts of the repowering process. A key finding was that repowering significantly enhanced turbine efficiency and extended their operational lifespan. Additionally, the study highlighted the environmental benefits of repowering low-capacity wind turbines nearing the end of their lifecycle.

(Serri, et al. 2018) outlined three potential pathways for wind farms at the end of their operational life: decommissioning, revamping, and repowering. Among these, repowering was identified as the optimal solution due to its numerous advantages, such as improved wind energy utilization, reduced turbine numbers, and minimized land use.

(Piel, et al. 2019) conducted a feasibility assessment of repowering and life extension for wind turbines, addressing challenges related to optimal life extension. Similarly, (Syed, et al. 2020) analysed the partial repowering of onshore wind farms affected by wake degradation from upstream turbines, concluding that repowering significantly increased energy production.

(Castro, et al. 2011) found that replacing older wind turbines led to greater energy production, with investment recovery achievable within five years. (Vicente-Ramírez, et al. 2019) performed a technical evaluation, revealing that repowering projects yielded satisfactory productivity with a payback period of less than six years.

(Carvalho, Guardia and Lima 2019) studied the integration of PV plants with wind farms. While wind farms alone demonstrated economic viability, the addition of PV systems reduced the likelihood of achieving positive net present value (NPV). However, the study concluded that integrating the two systems enhanced overall business potential.

(Filgueira, et al. 2009) examined the technical and financial aspects of repowering the wind farms at Bustelo and S. Xoán in Galicia, a region with exceptional wind energy potential. Commenced in 1998, both farms share similar characteristics, including location, generator type, and substations, allowing for both joint and independent analysis.

The study's findings indicate that repowering is a profitable undertaking, with investment recovery achievable within five years. This profitability stems from the substantial increase in energy production per generator, resulting from more efficient utilization of the site's wind resources and advancements in technology. The study underscores the economic viability and enhanced resource optimization achieved through repowering.

The operational lifespan of numerous wind farms is approaching its end, prompting national power systems to confront critical decisions in the coming years: whether to repower these facilities or to dismantle the existing wind turbines partially or fully. To address this challenge, (Gil-García, et al. 2022) introduced an updated methodology for assessing the feasibility of wind farm repowering. The proposed approach considers a comprehensive set of factors often integral to decision-making, including climatic, technological, environmental, social, and economic aspects. These factors are systematically analyzed and optimized using various multi-criteria evaluation methods to support informed decision-making.

In India, repowering older wind farms has gained attention as a strategy to enhance RE output without requiring additional land. Studies have shown that replacing old low-capacity turbines with modern, high-capacity models can significantly boost energy generation. In Tamil Nadu, wind farms built in the early 2000s have reached the end of their operational lifespan. These turbines, located in high-potential wind zones, face the choice of either dismantling or repowering. The land between turbines, arranged in a 5Dx7D configuration, presents significant underutilized areas. (Boopathi, Ramaswamy and Kirubaharan, et al. 2020) explored refurbishing outdated turbines and constructing solar power plants in these vacant spaces to maximize resource utilization.

The focus of the investigation was a 6 MW wind farm in Kayathar, Tuticorin District, Tamil Nadu. Energy estimates were calculated using WAsP and PVSyst software tools. Analytical results demonstrated that replacing older turbines with modern, higher-capacity turbines increased power production from 3.50 GWh to 40 GWh at a P90 confidence level, with a repowering capacity ratio (RCR) ranging from 1:1.25 to 1:3 and a renewable energy yield ratio (REYR) from 1:1.61 to 1:7.82. The integration of repowered wind turbines with solar power systems has resulted in significant increases in annual energy production, ranging from 38 to 76 GWh/year, underscoring the potential of hybrid electricity as a reliable and efficient energy source.

Furthermore, (Boopathi, Ramaswamy and Kirubakaran, et al. 2021) conducted an economic analysis of a wind farm located in Kayathar by replacing 30 outdated 200 kW wind turbines with modern 2000–3000 kW turbines and installing a solar power plant between the turbines while excluding the shadow region. The analysis utilized HOMER Pro software and Excel spreadsheet to evaluate optimal system allocation, electricity production, economic viability, and sensitivity.

Electricity pricing was assessed using levelized cost of energy (LCOE) and NPV methodologies. Additionally, sensitivity analyses were performed to estimate the impact of parameters on the Internal Rate of Return (IRR) and debt service coverage ratio for wind-solar hybridization. The results indicate satisfactory profitability for the project, even without reliance on subsidies. Sensitivity analysis further highlights the potential risks to the wind farm's lifecycle and their effects on the project's overall productivity and performance.

(Goyal 2010) analyzed various constraints affecting the repowering of wind energy projects in India, including inadequate tariffs, non-uniform state policies, and insufficient evacuation infrastructure. Their study also examined the wind energy market and highlighted the potential opportunities for repowering within the Indian wind energy landscape.

The MNRE has set guidelines for repowering wind turbines with capacities of 2 MW or less, aiming to encourage the deployment of larger, more efficient turbines. By allowing extended PPAs for repowered projects, the MNRE expects to incentivize wind energy producers to modernize their installations. Additionally, case studies from other countries demonstrate that similar policies can yield substantial energy and economic benefits, underscoring the need for strong regulatory support.

1.2 Objective

This report aims to evaluate the repowering potential of the Chalkewadi wind farm under standalone and hybrid scenarios. To achieve this, an optimization algorithm was developed that also models the constraints outlined in the MNRE guidelines for repowering. The algorithm focuses on maximizing energy output. The study's broader objectives are as follows:

- To identify the challenges, feasibility and potential benefits associated with repowering.
- To analyze the factors influencing decisions in repowering projects.
- To assess the policy, regulatory, and environmental requirements necessary for successful repowering.

1.3 Challenges and Benefits of Repowering

Repowering India's wind farms offers an estimated potential of 25.4 GW, according to the National Institute of Wind Energy (NIWE). To be viable, repowered projects are required to increase energy generation by at least 1.5 times compared to the original output (MNRE 2023). This initiative is essential to revitalizing the wind sector. However, repowering faces several challenges, including spacing criteria due to larger turbines, land and ownership issues, decommissioning costs, and regulatory considerations. Some of the associated unique challenges are listed below:

- **Financial Challenges**: The substantial initial capital investment required for wind farm repowering often discourages owners from proceeding, especially when their existing turbines are still generating profits.
- **Ownership Concerns**: Reducing the number of turbines during repowering can leave some individual owners without a turbine altogether, leading to potential disputes.

- **Land Constraints**: New micro-siting often necessitates relocating some turbines to new sites, requiring the sale of older turbine footprints and the acquisition of additional land.
- **Decommissioning Costs**: The expense of dismantling existing turbines should be considered, alongside costs for updating access roads, grid infrastructure, and related facilities.
- **Power Evacuation Challenges**: Many older turbines are connected to overloaded distribution substations. New infrastructure is required to handle the increased power output from repowering, thereby necessitating grid reinforcement for power evacuation at higher capacity and possibly at higher voltage levels.
- **PPA Challenges**: Earlier PPAs were signed at higher tariffs with more favorable wheeling and banking conditions. In contrast, currently distribution companies are opting to purchase power at lower prices, resulting in additional challenges for repowering projects.
- **Regulatory Gaps**: Lack of clear policies and regulatory guidelines, particularly around turbine disposal, poses significant environmental and operational challenges.

Repowering WPPs also offers numerous benefits across technical, financial, social, and environmental categories.

- **Technical**: Repowering increases energy generation per unit area by replacing older, smaller, less efficient turbines with newer, larger models that are more efficient with higher CUF. Unlike old wind turbines, modern wind turbines are more grid friendly and comply with grid connection regulations. Advances in artificial intelligence (AI) and machine learning also enhance turbine micro-siting, improving energy production.
- **Financial**: In addition to the increased energy generation and accordingly increased revenue, repowering reduces operational and maintenance costs by replacing frequently maintained, older turbines with more reliable ones that require fewer visits and have fewer moving parts. Additionally, the decommissioned turbine components can provide monetary benefits through recycling, and existing infrastructure such as grid connections can be leveraged.

- **Social**: Repowering minimizes land acquisition challenges, as the turbines are often replaced on already established sites, and it creates jobs within the RE sector.
- **Environmental**: repowering leads to a reduction in noise levels by replacing many smaller turbines with fewer, larger ones, and it helps reduce the fatality of avian creatures by using turbines with lower operating speeds. Moreover, increased energy yield from modern repowered wind turbines leads to an increased share of overall electricity from RE, thereby reducing the carbon emission indirectly from the replaced conventional generation.

This comprehensive set of benefits underscores the potential of repowering to enhance the efficiency and sustainability of wind power generation.

1.4 Eligibility Criteria of Repowering

MNRE has outlined specific eligibility criteria for wind turbines to qualify for repowering or refurbishment under its policy. Wind turbines that meet the following conditions are eligible:

- Turbines that are not in compliance with the quality control orders issued by the Ministry.
- Turbines that have completed their design life, as certified under the Type Test Certificate in accordance with applicable standards.
- Turbines with a rated capacity below 2 MW.
- Turbines connected to a single Polling Sub Station (PSS).
- Turbines that are considered based on commercial or voluntary considerations after 15 years of installation.
- Wind power Project with adjacent land area.
- Additionally, turbines that experience malfunctions, workmanship issues, or safety concerns during their design life are also required to be repowered or refurbished.

The above-mentioned criteria are aimed at ensuring that older, less efficient turbines can be upgraded, improving overall performance, and contributing to the sustainability of the wind energy sector.

1.5 Repowering Policies

In August 2016, MNRE introduced its Repowering Policy, applicable to wind turbine generators (WTGs) with capacities of 1 MW or less. The policy included several key provisions:

- The Indian Renewable Energy Development Agency (IREDA) would offer an additional 0.25% interest rate rebate.
- State transmission utilities would handle any required augmentation of the transmission system from the pooling station onward.
- For PPAs with state distribution companies (DISCOMS), the power generated equivalent to the average of the last three years' generation prior to repowering would continue under the existing PPA terms, while the additional generation could be sold to DISCOMS at the prevailing feed-in tariff or through third-party sales.
- Wind farms or turbines undergoing repowering would be exempted from PPA obligations for generation shortfalls during the repowering period. Captive users undertaking repowering would be allowed to purchase grid power during the repowering phase, subject to regulator-determined charges.

1.6 Decommissioning

The expected useful life of a wind farm is typically around 20 years. As wind energy installations have been steadily increasing since the early 2000s, many existing wind farms have already reached, or are soon approaching, the end of their operational life. Consequently, wind farm owners should evaluate their options: extend the operational life, repower the site, or decommission the turbines.

Decommissioning is essential upon completion of the turbines' designed lifespan to avoid potential safety hazards. However, in India, many older wind farms have surpassed their 20-year design life yet continue to operate because they remain financially viable for their owners. This situation raises national concern, as these outdated installations utilize valuable windy sites inefficiently, operating with a much lower CUF compared to modern turbines.

For repowering projects, the decommissioning of old WTGs requires a thorough analysis of several factors, including the residual value of the existing turbines. Options such as scrap value, manufacturer buy-back programs, or relocation of the turbines may be considered. While dismantling older wind farms, some components, such as metals, can be recycled, but disposing of non-recyclable parts, like blades, can pose challenges.

Decommissioning for repowering requires careful consideration of environmental, social, and economic factors as described below:

- **Environmental Impact Assessment (EIA):** Conduct an EIA to identify potential risks such as soil erosion, water contamination, and habitat loss. Propose mitigation measures to address these issues before decommissioning begins.
- **Permissions and Site Preparation:** Obtain necessary permits from regulatory authorities. Remove all non-reusable infrastructure, including buildings, wires, transformers, and foundations, ensuring the site is cleared of debris.
- **Waste Management:** Manage waste materials like metals, concrete, polymers, and hazardous substances by sorting, transporting, and disposing of them in compliance with local regulations and best practices.
- **Land Restoration:** Restore the site to its original state by removing all structures, restoring the land, and planting vegetation to prevent erosion and retain soil moisture. Follow EIA guidelines and local requirements.
- **Health and Safety:** Ensure worker safety by providing proper training, equipment, and maintenance during the decommissioning process. Follow strict safety protocols to minimize risks.
- **Community Engagement:** Engage with the local community and stakeholders to address concerns, provide updates, gather input on land rehabilitation, and future use of the site.

Decommissioning involves the safe removal of all old equipment and infrastructure, adhering to environmental, social, and safety standards. This process is essential for repowering, as it clears the site for new installations.

Pre-Decommissioning Planning

A comprehensive site assessment should be conducted to evaluate the existing WTGs, considering their age, condition, and structural integrity. Additionally, an inventory of components, including blades, nacelle, tower, foundation, and electrical systems, should be documented to ensure proper handling, disposal, or potential reuse. Furthermore, all necessary permits and approvals should be obtained from central, state, or local authorities, and other relevant regulatory bodies to ensure compliance with legal and environmental requirements.

Dismantling Process

The decommissioning process begins with electrical disconnection, where the WTGs are safely disconnected from the grid, ensuring all electrical systems are de-energized before removing transformers, cables, and other electrical components. Next, blade removal is carried out using cranes and specialized equipment to carefully detach and lower the blades, which may be cut into manageable sections for transportation if necessary. The nacelle, housing the gearbox, generator, and control systems, is then dismantled and lowered using cranes. Following this, the tower is sectioned into smaller pieces using cutting tools and safely lowered to the ground. The foundation is excavated and removed, with efforts made to reuse or recycle the concrete whenever possible. Finally, all dismantled components are transported to designated recycling or disposal facilities, ensuring environmentally responsible handling of materials. The decommissioning implementation road map is outlined in Table *1*.

Table 1: Decommissioning Implementation Roadmap

Phase	Activities	Timeline
Planning	Site assessment, permits, and approvals	1-2 months
Dismantling	Electrical disconnection, blade, nacelle, and tower removal	2-3 months
Waste Management	Recycling, disposal, and inventory tracking	1-2 months
Site Restoration	Soil remediation, revegetation, and erosion control	2-3 months
Monitoring	Post-restoration monitoring and reporting	1-2 years

Environmental Remediation Strategies

To ensure environmental protection during decommissioning, soil and water protection measures should be implemented. This includes soil testing for potential contamination from oil, grease, or heavy metals due to WTG operations, followed by appropriate remediation techniques such as bioremediation or soil washing. Additionally, water management strategies should be in place to prevent runoff from contaminated sites and treat any polluted water. Waste management should adhere to regulatory guidelines, ensuring hazardous waste, including lubricants and batteries, is disposed of in compliance with the Hazardous and Other Wastes (Management & Transboundary Movement) Rules, 2016, while non-hazardous materials like steel, copper, and concrete may be recycled or reused. To mitigate environmental impact, noise and dust control measures should be implemented, such as using water sprays and noise barriers to minimize disturbances during dismantling activities.

Material Management Plans

A sustainable recycling and reuse strategy should be implemented to minimize waste and maximize resource recovery. Blades, made of composite materials, can be processed using pyrolysis or mechanical recycling techniques. Metals such as steel, copper, and aluminum from towers, nacelles, and electrical systems may be recovered and recycled, while concrete from foundations can be crushed and repurposed for road construction or other infrastructure projects. Any non-recyclable materials may be disposed of in accordance with the Solid Waste Management Rules, 2016, ensuring environmental compliance. Additionally, a detailed inventory should be maintained to track materials throughout the decommissioning process, facilitating efficient reporting and resource management.

Regulatory Compliance Mechanisms

To ensure regulatory compliance, environmental clearance should be obtained under the EIA Notification, 2006, before proceeding with decommissioning activities. Waste management should adhere to the Hazardous and Other Wastes (Management & Transboundary Movement) Rules, 2016, and the Solid Waste Management Rules, 2016, ensuring proper disposal and recycling of materials. Additionally, health and safety protocols may be followed in accordance with the Factories Act, 1948, and the Occupational Safety, Health and Working Conditions Code, 2020, to protect workers during dismantling operations. Furthermore, land use regulations should be met as per the Forest (Conservation) Act, 1980, and the Panchayati Raj Act (if applicable), ensuring legal compliance in land repurposing or restoration efforts.

Reporting and Documentation

Decommissioning plans and progress reports should be submitted to the MNRE, State Nodal Agencies, and Pollution Control Boards to ensure regulatory compliance and transparency. Additionally, detailed records of waste disposal, recycling, and site restoration activities should be maintained, facilitating proper documentation and adherence to environmental and operational standards.

Site Restoration Approaches

A comprehensive land rehabilitation plan should be implemented to restore the site post-decommissioning. Revegetation efforts should focus on planting native vegetation to restore ecological balance, while erosion control measures such as terracing and mulching should be employed to prevent soil degradation. Additionally, all temporary structures, access roads, and fencing should be removed, unless required for the repowered project. Community engagement is essential, involving local stakeholders in restoration activities to ensure social acceptance and long-term sustainability. Finally, post-restoration monitoring should be conducted for 1-2 years to assess soil stability, vegetation growth, and overall site conditions, addressing any emerging issues such as soil erosion or inadequate plant regeneration.

Decommissioning costs

Decommissioning costs include expenses related to dismantling wind turbines, clearing the site, and safely disposing of blades and other materials. Efficient decommissioning not only mitigates safety risks but also opens opportunities to harness the full potential of wind energy at repowered sites.

$$Decommissioning\ cost = DS + SC + DB - SM$$

Where,

- DS - Cost incurred for dismantling Wind turbine
- SC - Cost incurred for clearing the site
- DB - Cost incurred for disposal of blades
- SM - Income from sale of scrap material

The detailed analysis of decommissioning costs is presented in section 10.1.3.

2 Wind Energy in Maharashtra

As of August 2024, Maharashtra had an installed power capacity of 47.3 GW, solidifying its position as India's second-largest power-generating state, second only to Gujarat. Coal dominates the energy mix, accounting for 51% (24 GW) of the state's capacity. Gas and hydroelectric power contribute 7% and 6%, respectively, while nuclear energy represents a modest 3% (1.4 GW). Renewable energy sources make up the remaining 33% of the state's capacity, highlighting Maharashtra's growing emphasis on clean energy initiatives (see Figure 2).

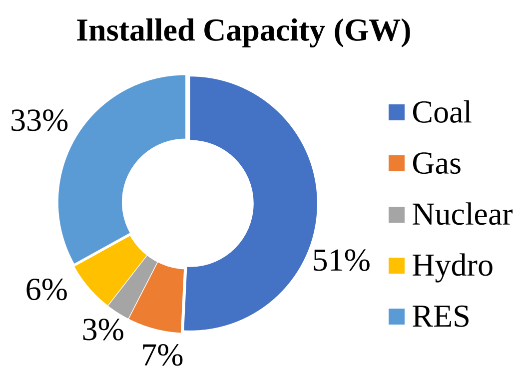

Figure 2: Installed capacity mix of Maharashtra as in August 2024 *(CEA Dashboard 2024)*

Wind energy generation in Maharashtra initiated in 1986 in the coastal region of Ratnagiri with 55 kW Vestas WTGs. The state's continuous expansion of wind energy in its installed capacity highlights its strong commitment to advancing renewable energy generation and fostering sustainable development (see Figure 3). Although subsequent developments have seen an increase in turbine capacities, older machines remain operational despite being significantly outdated compared to modern WTGs. Despite having surpassed their intended life cycle, these turbines continue to remain operational. Over the past three decades, advancements in technology have created a significant opportunity to replace older, low-capacity wind turbines with modern, high-capacity models featuring improved CUF. The currently operational turbines in the state range from capacities below 0.5 MW to modern installations exceeding 2 MW, showcasing the significant technological advancements achieved in the wind energy sector (see Figure 4).

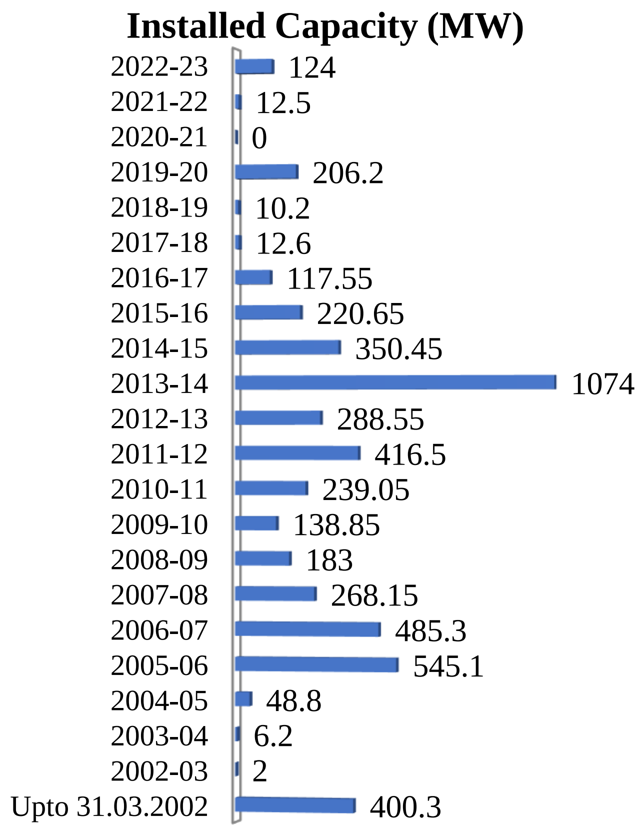

Figure 3: Installed capacity expansion of Maharashtra *(NIWE, https://niwe.res.in/ 2024)*

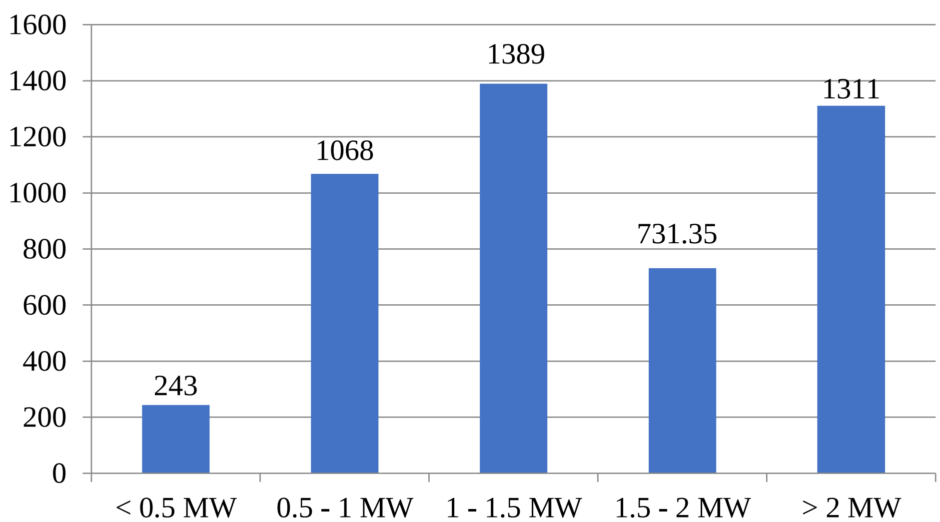

Figure 4: Installed capacity range of WTGs in Maharashtra *(MNRE 2022)*

3 Site Description and Micro-Siting

3.1 Site Description

The Chalkewadi Wind Farm, located at latitude 17° 37’ 25” N and longitude 73° 48’ 41” E, is situated approximately 30 kilometers from the town of Satara in one of the windiest regions of Maharashtra. The wind farm and its boundaries, highlighted in red, are depicted using Google Maps (see Figure 5). It is positioned at an elevation of 1,185 meters above sea level. Currently, the site is equipped with 8 WTGs, each with a capacity of 250 kW, totaling an installed capacity of 2 MW. Repowering efforts are underway to replace these turbines with higher-capacity models, aiming to significantly boost energy production and enhance operational efficiency.

Figure 5: Chalkewadi wind farm (Google Earth)

3.2 Wind Speed

Figure 6 illustrates the monthly mean wind speed at heights of 100 m and 120 m. The hourly wind speed data at 100 m and 120 m heights for the year 2014 was obtained from National Renewable

Energy Laboratory (NREL) for the Chalkewadi site. This data was utilized to generate Figure 6. Table 2 presents detailed meteorological parameters for Chalkewadi at a height of 120 m, including the corresponding Weibull parameters, "k" and "A." The site benefits from a mean annual wind speed of 7.69 m/s and a mean annual wind power density of 473.62 W/m² measured at 120 meters, providing optimal conditions for wind energy generation (NIWE 2025). In the graph, the horizontal axis represents the months, while the vertical axis denotes wind speed in meters per second. The monthly average trends indicate a significant rise in wind resources, particularly wind speed, from May to September. This noticeable increase is primarily driven by the southwest monsoon, a dominant meteorological phenomenon influencing southern India.

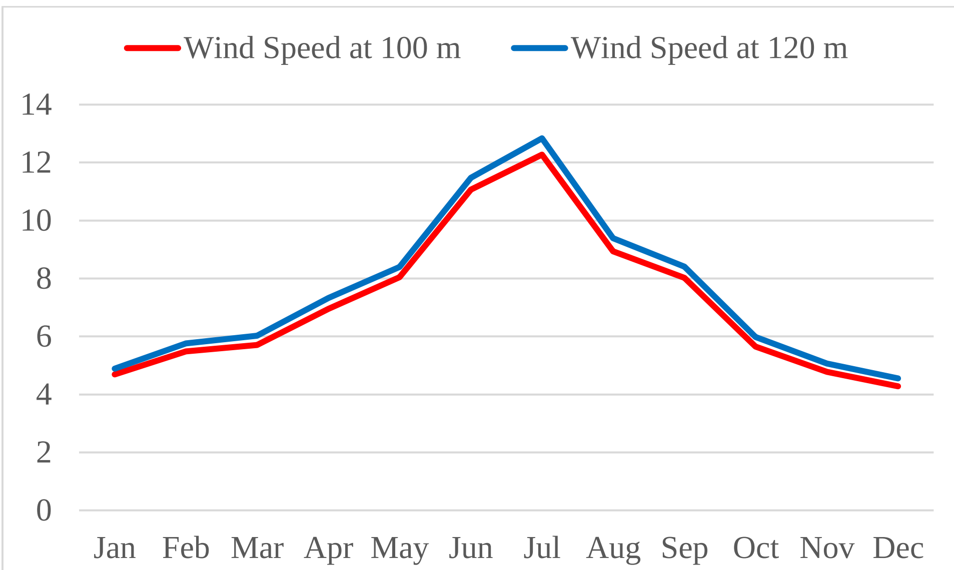

Figure 6: Monthly mean wind speed at 100 m and 120 m in Chalkewadi

Table 2: Meteorological parameters for the Chalkewadi site

Location	Wind Speed (m/s)	Weibull A (m/s)	Weibull K	Air Density (kg/m^3)	Wind Power Density (W/m^2)
Chalkewadi	7.69	8.672	1.927	1.049	473.62

3.3 Wind Direction

Similarly, hourly wind direction data was obtained from NREL and used as the primary source for generating wind rose diagrams for the Chalkewadi site. Figure 7 presents the wind rose diagram, systematically divided into 16 sectors, each spanning 22.5-degree intervals. These diagrams depict wind speeds for each cardinal direction using color-coded segments, accompanied by detailed legends for clarity.

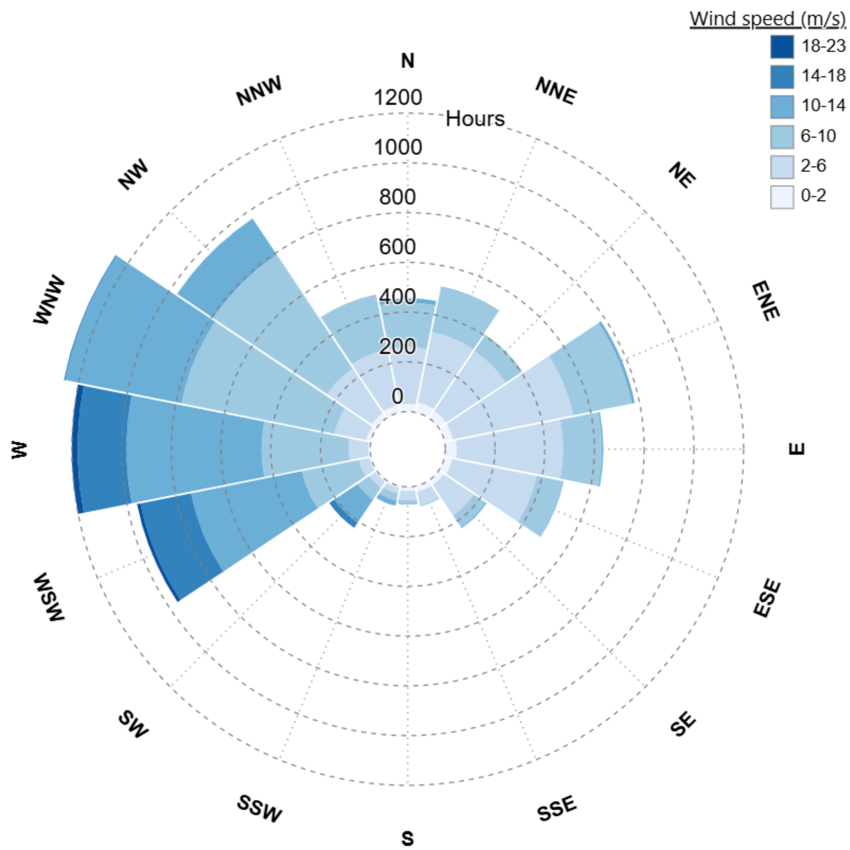

Figure 7: Wind rose at 50 m height for Chalkewadi

The predominant wind direction in Chalkewadi originates from the west. This information is crucial for optimizing wind farm (WF) design, as it helps determine the ideal placement of WTGs and ensures optimal turbine spacing for maximum efficiency.

3.4 Micro-siting

Micro-siting involves the strategic placement of WTGs within a wind farm to maximize energy production while considering all physical constraints of the area (MNRE 2016). Effective micro-sitting is crucial for optimizing the performance and efficiency of wind farms, ensuring that turbines operate under ideal wind conditions with minimal interference from surrounding structures and terrain features. The prescribed micro-siting criteria are as follows:

- **Optimization of Turbine Locations**: WTGs placements shall be optimized within owners' land using suitable wind flow modelling and optimization tools (linear and non-linear techniques). This process should include site assessments in accordance with the IEC 61400-1 standard for turbine safety, considering factors such as extreme wind conditions, flow inclination, vertical wind shear, turbulence with added wake effects, and corrections for terrain complexity.
- **Boundary Distance Requirements**: keep a distance of **3 × D** (where **D** is the rotor diameter) perpendicular to the predominant wind direction and **5 × D** in the predominant wind direction from the boundary line of each adjoining land owned by other developer(s), with proper offsets.
- **Wake Loss Management**: ensure the wake loss (in terms of energy) between WTGs does not exceed **10%**, with proper offsets when turbines are sited on a footprint basis.
- **Setback Distances from Infrastructure**: maintain a distance of **HH + ½ RD + 5 meters** (where **HH** is the hub height and **RD** is the rotor diameter) from public roads, railway tracks, highways, buildings, public institutions, and extra-high voltage (EHV) lines.
- **Noise Mitigation**: do not site WTGs within **500 meters** of any dwelling to mitigate noise impacts.

This micro-siting technique ensures optimized utilization of land with wind resources, maximizing energy production while adhering to safety and environmental standards.

4 Legal Issues

Repowering projects involves replacing older, smaller wind turbines with higher-capacity WTGs, which presents several legal issues, particularly concerning land requirements. Higher-capacity WTGs typically have larger rotor diameters and taller towers, necessitating more land for installation and ensuring safe distances between turbines to avoid wake effects. This increased land requirement can lead to legal challenges, especially in areas where land ownership is fragmented or where land use is restricted due to environmental or regulatory constraints.

Under the Indian legal framework, land acquisition for wind energy projects is governed by state-specific policies and central laws such as the Right to Fair Compensation and Transparency in Land Acquisition, Rehabilitation and Resettlement Act, 2013 (LARR Act). Repowering projects may require additional land, which could involve renegotiating land leases or acquiring new land, both of which can be legally complex and time-consuming. Furthermore, revised micro-siting is essential to accommodate the larger footprint of higher-capacity WTGs, ensuring compliance with setback requirements, environmental regulations, and grid connectivity norms. This process may involve obtaining fresh clearances from state authorities and adhering to guidelines from the MNRE and the CEA. Addressing these legal issues requires careful planning, stakeholder consultation, and alignment with existing land and environmental laws to ensure the successful implementation of repowering projects.

Land Requirement Issues

Repowering with higher-capacity WTGs introduces legal considerations related to land use and ownership. These turbines have larger rotor diameters and taller towers, increasing the land footprint and necessitating greater spacing between turbines to mitigate wake effects. Many existing wind farms operate on leased land, meaning repowering may require renegotiating leases or acquiring additional land, which can be legally complex. Furthermore, land located in ecologically sensitive areas or near forests may be subject to restrictions under the Forest

(Conservation) Act, 1980, or local zoning regulations, requiring careful legal assessment and compliance with environmental laws.

Mitigation procedures for land acquisition should include land pooling and consolidation, where collaboration with landowners helps merge land parcels to meet increased requirements. Additionally, lease renegotiation should be conducted to ensure fair terms, aligning with the Right to Fair Compensation and Transparency in Land Acquisition, Rehabilitation, and Resettlement Act, 2013 (LARR Act). Furthermore, state-specific wind energy policies should be leveraged to streamline the land acquisition and leasing process, facilitating smoother development of RE projects.

Micro-Siting Issues

Legal considerations for repowering include setback requirements, as higher-capacity WTGs necessitate revised micro-siting to maintain adequate distances from roads, buildings, and infrastructure. Additionally, these adjustments may impact ecologically sensitive areas or local communities, requiring fresh environmental and social impact assessments to address potential concerns. Furthermore, the new micro-siting layout should comply with grid connectivity standards established by the CEA to ensure seamless integration into the power network.

Effective mitigation procedures should be implemented to ensure sustainable WF repowering development. This includes conducting detailed site surveys to identify optimal WTG locations, considering environmental, social, and technical factors. If the revised micro-siting impacts ecologically sensitive areas, obtaining fresh environmental clearances under the EIA Notification, 2006, is essential. Additionally, stakeholder consultation should be conducted to engage with local communities and relevant stakeholders, addressing concerns and ensuring compliance with social impact assessment (SIA) requirements.

Environmental and Regulatory Compliance Issues

Repowering projects should address several legal and regulatory considerations, including environmental clearances, which may be required if the project involves significant changes in scope or location. Additionally, projects situated near forest areas or wildlife habitats should comply with the Forest (Conservation) Act, 1980, and the Wildlife Protection Act, 1972, ensuring minimal ecological impact. Furthermore, the integration of higher-capacity WTGs should adhere to the Indian Electricity Grid Code (IEGC) and technical standards for grid connectivity, ensuring seamless power evacuation and compliance with national regulations.

To mitigate potential challenges, early clearance applications for environmental, forest, and wildlife approvals should be submitted during the planning stage to prevent project delays. A comprehensive monitoring and reporting system should also be implemented to track environmental and social impacts, ensuring continuous adherence to regulatory requirements. Additionally, the revised project design should comply with the IEGC and CEA standards to ensure seamless grid connectivity.

Decommissioning Issues

Legal compliance in waste management is crucial during decommissioning, as it generates fiberglass, metals, and electronic waste, all of which should be handled in accordance with the Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016. Additionally, land restoration is essential, ensuring that areas previously occupied by turbines are either returned to their original condition or repurposed for new wind energy installations, maintaining environmental and regulatory standards.

Effective mitigation procedures should be implemented to minimize environmental and social impacts during decommissioning. This includes developing and executing waste management plans in compliance with applicable regulations, ensuring land restoration or repurposing aligns with environmental and land use guidelines, and actively engaging local communities to address concerns and maintain transparency throughout the process.

Financing and Incentives

Repowering projects should navigate key legal and financial considerations, including Viability Gap Funding (VGF) under the central or/and state government scheme, which requires adherence to specific eligibility criteria and reporting requirements. Additionally, to maximize tax and depreciation benefits, projects should comply with relevant tax laws and depreciation rules outlined in the Income Tax Act, 1961, ensuring financial feasibility and regulatory compliance.

As part of mitigation procedures, detailed project proposals should be submitted to the central or/and state government scheme for VGF applications, ensuring compliance with eligibility criteria and proper documentation. Additionally, tax planning should be conducted in collaboration with financial and legal experts to optimize tax and depreciation benefits under the Income Tax Act, maximizing financial efficiency for the project.

Repowering wind energy projects involves navigating a complex legal landscape, including land acquisition, environmental clearances, revised micro-siting, and regulatory compliance. Mitigating these challenges requires a structured approach, including stakeholder engagement, early clearance applications, and adherence to regulatory frameworks. By addressing these legal issues proactively, repowering projects can contribute significantly to India's RE goals while ensuring environmental and social sustainability.

5 Economic Analysis

5.1 Financial Modeling of Repowering

An economic analysis of wind farm repowering involves evaluating the financial costs and benefits associated with its construction, operation, and maintenance. This analysis considers factors such as the initial capital expenditure, operational costs, and the revenue generated from selling the produced electricity. It may also include examining how the project's financial performance is affected by changing economic and market conditions. The primary income for a wind farm is typically derived from the export value, which is the price of electricity sold to the electrical grid. In this context, an electricity price of 5000 ₹ $/MWh$ under the "Feed-in Tariff" scheme is assumed.

This study evaluates the repowering potential of wind farms using the following key performance metrics: LCOE, IRR, NPV, and Discounted Payback Period (DPP). These metrics provide a comprehensive analysis of the economic viability and financial performance of the repowered wind farm.

5.1.1 Weighted Average Cost of Capital (WACC)

As per the funding guidelines for private sector wind generation projects (PFC 2025), Power Finance Corporation (PFC) offers financial support to such projects under the following conditions:

- The project should have a firm PPA with State or Private DISCOMs, or any other approved Government or Private entity. Additionally, projects where the State Electricity Regulatory Commission (SERC) has approved a Feed-In-Tariff, but the PPA is yet to be signed may also be considered.
- Projects intended for captive consumption should be established either through a SPV or directly on the end consumer’s balance sheet, subject to specific conditions.

PFC typically finances projects with an installed capacity of at least 10 MW, covering up to 50% of the total project cost. However, it may also function as the sole lender if required. Using high-capacity factor turbines can reduce the Weighted Average Cost of Capital (WACC) by enabling greater debt financing. Since the cost of equity is higher than debt, maximizing the debt portion is advantageous for wind projects (Maidl 2025). As per the guidelines, the Debt-to-Equity (D/E) ratio should not exceed 75:25, ensuring that the equity contribution is at least 25% of the total project cost. The WACC can be calculated as:

$$WACC = \left(\frac{E}{V} \times R_e\right) + \left(\frac{D}{V} \times R_d \times (1 - Tax\ rate)\right)$$

Where:

E: Market value of equity

D: Market value of debt

$V = E + D$: Total capital

R_e: Cost of equity (expected return on equity)

R_d: Cost of debt (interest rate on debt)

$Tax\ Rate$: Corporate tax rate

In India, wind energy projects benefit from various incentives, including a 10-year income tax holiday, which impacts the tax rate used in the WACC calculation, as well as duty exemptions (SAS Partners 2025). The cost of equity can be determined by using the Capital Asset Pricing Model (CAPM):

$$R_e = R_f + \beta\left(R_m - R_f\right)$$

Where:

R_f: Risk-free rate

$R_m - R_f$: Market risk premium (MRP)

β: Beta

These parameters are not easily determined directly. However, the R_f can be estimated using government bonds as a benchmark. In India, the yield on a 10-year government bond is approximately 7–7.5% based on recent data, so 7.5% is used for calculation. The β for renewable energy projects generally falls within the range of 0.8 to 1.2, and assuming β = 1.0, with the MRP in India typically between 6–7%, we take 6.5% as a reference. Thus, R_f is calculated as 14%.

With government incentives and stronger financial performance of original equipment manufacturers (OEMs), the R_d is estimated to be in the range of 8–10%. Assuming a pre-tax R_d of 9%, if the project falls within the tax holiday period, the effective tax impact is zero. Otherwise, with India's corporate tax rate typically ranging from 25% to 30%, we assume a 25% rate. Based on these assumptions, the WACC is calculated to be 8.56%.

For wind repowering projects, the WACC is a key factor in assessing project feasibility. A lower WACC reduces the required return threshold, enhancing the attractiveness of investments. The calculated WACC acts as the discount rate, used to determine the present value of future cash flows in financial modeling and project valuation. It reflects the project's overall cost of capital, integrating both debt and equity financing while considering the tax advantages associated with debt.

5.1.2 LCOE

The LCOE determines the average cost per unit of electricity generated over the lifetime of the repowered wind farm. It accounts for all costs incurred during the project's lifetime, including the initial capital investment, operation and maintenance expenses, and land compensation. This metric is useful for comparing the cost-effectiveness of different energy generation technologies.

$$LCOE = \sum_{t=1}^{T} \left(\frac{\left(\frac{I_t + M_t + L_t}{(1 + r_{DR})^t} \right)}{\left(\frac{E_t}{(1 + r_{DR})^t} \right)} \right)$$

where,

$LCOE$: Levelized cost of energy of the repowered wind farm $(₹/MWhr)$

I_t : Capital annuity $(₹/yr)$

M_t: Annual maintenance and operation cost $(₹/yr)$

L_t: Land compensation cost $(₹/yr)$

E_t: Annual energy evacuated to a Grid $(MWhr)$

T: Lifetime of a wind turbine in years (yr)

r_{DR}: Discount rate of the project

The repowered project's lifespan is assumed to be 20 years, with a discount rate calculated as 8.56%. The initial capital cost of the wind farm can be determined by multiplying the turbine rating, the number of turbines, and the unit annual expenditure. This calculation is given by the formula:

$$Capital\ Cost = \sum_{i=1}^{n} X_i C_{CAPEX} P_i$$

Where:

$Capital\ Cost$: Initial capital required to construct the wind farm (₹)

C_{CAPEX}: Annual expenditure of capital to produce a 1 kw in the lifespan of the wind farm $(₹/kW)$

The initial capital investment encompasses the costs associated with roads and civil works, transportation, as well as the assembly and installation of the wind turbines. In India, the capital cost for wind farms generally ranges from 4.5 crores to 6.85 crores per megawatt, influenced by factors such as the type of turbine, the technology used, the scale of the installation, and its geographical location (Green World Investor 2024). In this study, we have considered the higher end of this cost range. Using general industry guidelines or rules of thumb, we can determine the unit annual expenditure for operation and maintenance with the following approach (Shaahid, Al-Hadhrami and Rahman 2014):

$$C_{OPEX} = 3\% C_{CAPEX}$$

Where:

C_{OPEX}: Annual expenditure of capital to operate and maintain a 1 kw power production in the lifespan of the wind farm $(₹/kW)$

Therefore, the annual operation and maintenance expenditure for the wind farm can be determined by calculating:

$$M_t = \sum_{i=1}^{n} X_i C_{OPEX} WTG_{Rating}$$

There are two methods for acquiring land for a repowering wind farm project: either purchasing the land outright or leasing portions of it from landowners, specifically the areas needed to build and assemble the powerhouse and towers. This research adopts the latter approach, as leasing reduces the initial capital expenditure by spreading the payments over the lifespan of the wind farm. The cost of acquiring private land for setting up wind energy projects in India generally falls between INR 15 lakh to 25 lakh per acre, contributing approximately 3% to 5% of the total project cost (Kumar and Thapar 2017). In this study, we have considered the higher end of this cost range. The annual land lease cost can be calculated by:

$$L_t = C_{LEX} * Area_{Occupied}$$

Where:

C_{LEX}: Annual expenditure of capital for lease of the land in the lifespan of the wind farm (₹$/hectare$)

The NPV is utilized to evaluate the profitability of the repowering project by determining the present value of anticipated future cash flows (inflows and outflows).

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1 + r_{DR})^t}$$

Where:

C_t: cash flows (₹)

If the NPV is positive, it indicates that the investment is expected to be profitable; conversely, a negative NPV suggests that the investment may result in a loss.

The IRR used to evaluate the profitability of the repowering project by determining the discount rate at which the NPV becomes zero. This represents the breakeven rate where the present value of future cash inflows equals the present value of cash outflows.

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1 + r_{IRR})^t} = 0$$

The DPP is used to determine the time required for the repowering project's discounted cash inflows to recover the initial investment, accounting for the time value of money.

$$DPP = No.of\ years\ before\ recovery + \frac{Remaining\ Cost}{Cash\ inflow\ in\ the\ following\ year}$$

5.2 Viability of Gap Funding

The primary challenge in repowering wind farms and upgrading related infrastructure lies in securing adequate financing. While such projects are often economically justified and socially beneficial, they may not always be financially viable. This results in a viability gap between the project's total cost and its projected cash flow or monetary returns. Even if the direct financial returns are less than the costs incurred, the broader societal benefits of these projects can be substantial. To address this issue and support project implementation, the government provides grants to bridge this viability gap.

To ensure the successful completion of such projects, the Indian government has introduced the VGF scheme, which operates under Public-Private Partnerships (PPPs) (Ministry of Finance 2020). VGF is a financial grant designed to support projects that are economically necessary but lack financial feasibility.

Repowering projects, which often require road development and strengthening to transport larger blades of modern turbines, as well as enhancements to power evacuation infrastructure to handle increased generation capacity, are eligible for VGF. Such eligibility falls under the consolidated list of sectors outlined in Annexure III, specifically under:

a) Roads, bridges, railways, seaports, airports, and inland waterways.
b) Power infrastructure.

Under the VGF scheme:

- The grant amount is determined based on the lowest bid for a capital grant, with a cap of 20% of the Total Project Cost (TPC).
- If additional financial assistance is provided by the sponsoring Central Ministry, State Government, or any statutory entity, it is capped at another 20% of the TPC.
- The combined VGF and supplementary assistance cannot exceed 40% of the TPC.

This framework ensures that repowering projects, despite their financial constraints, receive the necessary support to modernize infrastructure, improve efficiency, and deliver broader economic and social benefits.

Wind energy projects benefit from an 80% depreciation in the first year, effectively lowering taxable income and enhancing cash flow. Additionally, under Section 80-IA of the Income Tax Act, these projects are eligible for a 10-year tax holiday within the first 15 years of operation, further improving financial viability. Moreover, the concessional GST rate of 5% on wind turbine components helps reduce capital costs, making wind energy investments more cost-effective.

Structured Approach to VGF

A detailed cost-benefit analysis should be conducted to quantify the economic and social benefits of the project, ensuring that the VGF allocation aligns with the project's viability gap. Cost recovery mechanisms, such as revenue-sharing models or tariff adjustments, should also be explored to ensure long-term financial sustainability. These mechanisms can be integrated into the project's financial model to demonstrate how costs may be recovered over the project's lifecycle. The structured approach should include the following steps:

- **Gap Assessment**: Quantify the financial shortfall between project cost and anticipated revenue.
- **Funding Eligibility**: Evaluate project compliance with VGF eligibility criteria as per national renewable energy policies.

- **Funding Allocation**: Determine the VGF percentage based on the TPC, capped at a predefined maximum limit.
- **Disbursement Process**: Establish clear guidelines for phased VGF disbursement linked to project milestones such as financial closure, infrastructure upgrades, and commissioning.

In addition to VGF, other government schemes can provide financial support for repowering projects. These include central and state-level renewable energy incentives, subsidies for grid infrastructure upgrades, and grants under schemes like the Green Energy Corridor Project. The Green Energy Corridor Project, specifically, can support repowering by funding grid modernization and evacuation infrastructure, ensuring that the increased power generation capacity is efficiently integrated into the grid. Furthermore, alternative financial schemes such as multilateral financing from institutions like the World Bank or Asian Development Bank, green bonds, climate finance mechanisms like the Green Climate Fund (GCF), PPPs, development bank support, and the National Clean Energy Fund (NCEF) can be leveraged to bridge funding gaps. These avenues provide competitive interest rates, concessional financing, and additional capital, reducing the financial burden on developers and enhancing project viability.

A cost-sharing model between developers and utilities is essential for equitable fiscal responsibility. This model can be structured based on the benefits accrued to each party, with developers bearing the costs of turbine procurement and installation, while utilities contribute to grid upgrades and evacuation infrastructure. The Green Energy Corridor Project can further support this model by providing grants or low-interest loans for grid modernization, ensuring that the financial burden is shared, and the project remains viable. A general framework or protocol should be established to outline timelines, funding disbursement schedules, and project milestones. This framework should include a phased disbursement of VGF and other funds, tied to specific milestones such as financial closure, completion of infrastructure upgrades, and project commissioning. Regular monitoring and reporting mechanisms should also be incorporated to ensure transparency and accountability. The cost-sharing model framework should outline:

- **Proportional Contribution**: Define the percentage contribution from both parties based on installed capacity and grid requirements.

- **Grid Impact Assessment**: Evaluate the technical requirements and cost of infrastructure upgrades.
- **Agreement Framework**: Develop legally binding agreements detailing the cost-sharing structure, payment schedules, and operational responsibilities.

Funding avenues beyond government support, such as multilateral financing, green bonds, climate finance mechanisms, PPPs, development bank support, and the NCEF, can significantly enhance the financial viability of repowering projects. Multilateral financing institutions offer concessional loans and technical assistance, while green bonds provide access to capital markets at competitive rates. Climate finance mechanisms like the GCF focus on low-carbon projects, making them ideal for repowering initiatives. PPPs enable shared fiscal responsibility and risk mitigation, while development banks and the NCEF offer additional funding for clean energy projects. By integrating these funding sources into a comprehensive financial plan, repowering projects can achieve financial closure and ensure successful implementation.

A general protocol for implementing the financial framework should include the following stages:

- **Pre-Feasibility Study**: Identification of funding gaps and potential financing options.
- **Project Approval**: Submission of financial proposals and funding applications.
- **Milestone-Based Disbursement**: Disbursement of funds in stages, with 30% upon financial closure, 40% upon infrastructure completion, and 30% upon commissioning.
- **Monitoring and Compliance**: Regular project audits and financial reporting.
- **Final Evaluation**: Assessment of project outcomes and impact on grid stability and energy generation.

6 Repowering Optimization

Optimizing the repowering of a wind farm requires careful consideration of several factors, including the costs of equipment and installation, the expected increase in energy generation, and the overall optimization of the electrical system. The detailed mathematical modelling for this optimization is presented as follows:

Objective Function: the objective of the algorithm is to maximize energy generation,

$$Maximize \quad Z = \sum_{i=1}^{n} (X_i E_i)$$

Decision Variable: is turbines $X_{i,}$ which gives the number and type of turbines and E_i is the actual energy generated by WTG X_i.

By considering the objective function and decision variables, the following constraints are established for the repowering project to maximize energy generation from the wind farm.

Constraints:

1. In repowering, old wind turbines are replaced by new ones that have higher capacities and updated technology, thereby reducing the number of turbines needed to achieve the desired power generation. Thus, the optimization aims to install a minimal number of turbines compared to the existing generators. By optimizing the use of space on the wind farm, the algorithm determines the optimal number of turbines that maximize energy generation at the site. Therefore, the total number of turbines installed in the repowering project should be less than the number of turbines in the existing (old) wind farm.

$$\sum_{i=1}^{n} X_i \leq Turbines\ in\ Old\ WF \qquad (numbers)$$

2. According to the national repowering policy, the total capacity of the new turbines should be at least 1.5 times the capacity of the existing wind farm (MNRE 2023).

$$\sum_{i=1}^{n} X_i P_i \geq 1.5 * Installed\ Capacity\ of\ Old\ WF \qquad (MW)$$

where, P_i is the installed capacity of WTG X_i.

3. The total energy output of the repowered wind farm should be greater than that of the old wind farm.

$$\sum_{i=1}^{n} X_i P_i T CUF_i \geq Old\ WF\ Annual\ Energy\ Production\ Capacity \qquad (MWh)$$

where, CUF_i of X_i is a metric defined as the ratio of the actual energy output generated by the wind farm to the maximum possible energy output if the plant operated at its full installed capacity continuously during the same period. For annual calculations, T is typically 8,760 hours (the total number of hours in a year).

$$CUF_i = \frac{E_i}{P_i * T}$$

4. The required area to accommodate the repowered wind farm should be less than or equal to that of the old wind farm.

$$\sum_{i=1}^{n} X_i (3D_i\ x\ 5D_i)/10000 \leq Old\ WF\ Occupied\ Area \qquad (hectares)$$

where, D_i is the rotor diameter of WTG X_i.

5. The per unit cost of energy of the repowered wind farm should be less than or equal to that of the old wind farm.

$$\sum_{i=1}^{n} \left(\frac{Cost_i}{P_i TCUF_i} \right) \le P.u.cost\ of\ Old\ WF \qquad (₹/MWh)$$

where, $Cost_i$ is the cost associated (capital investment, O&M cost, …) of WTG X_i.

These five constraints are integrated into the algorithm of the repowering optimization tool to achieve optimal performance. In addition to these constraints, the algorithm efficiently calculates other electrical parameters using optimized computational methods. These calculations are based on standard methodologies, policy documents, and practical examples and case studies from repowering projects in wind farms. This comprehensive approach ensures that both the constraints and electrical parameters align with industry standards and best practices, resulting in an effective and reliable optimization process.

7 Power Evacuation and Infrastructure Planning

Power evacuation is a critical component in repowering projects, ensuring the seamless and efficient transfer of generated power to the electrical grid for distribution. Even the most advanced wind farms cannot contribute effectively to the grid without a reliable and well-designed power evacuation system. This process involves the development of substations, transmission, and distribution lines, and supporting electrical equipment that can manage the wind farm's power output efficiently and reliably.

With the integration of REs, which are often intermittent, and the need to optimize aging transmission infrastructure present unique challenges. A robust power evacuation system should address these by maximizing transmission capacity and managing the fluctuating nature of renewable generation. Optimizing existing transmission networks is essential to accommodate additional RE without compromising reliability, while the system should also be resilient enough to maintain grid stability despite the variability of wind power.

When designing a power evacuation system for repowering, several key considerations should be addressed.

- The system should be capable of managing the maximum power output of the wind farm, with equipment such as cables, transformers, and switchgear selected based on rigorous capacity calculations to avoid overloading or overheating.
- Cable routing should minimize losses and ensure operational safety.
- Transformers should be sized appropriately to step up the voltage for grid integration.
- Switchgear, including circuit breakers and disconnect switches, is essential for protecting and controlling the system, isolating faulty equipment when necessary to maintain uninterrupted operations.

A well-planned power evacuation system is fundamental to ensuring the efficient and reliable integration of wind energy into the power grid, enabling the growth of RE generation and contributing to a sustainable energy future.

Power evacuation calculations for repowering a wind farm involve several steps to ensure the generated power can be efficiently and reliably transmitted to the grid. The key calculations include:

- Determining the power evacuation of repowering

Power evacuation is estimated at 97%, with the remaining 3% accounted for as losses. Therefore, the power evacuated by the wind farm can be expressed using the following equation:

$$Power\ Evacuation = Installed\ Capacity\ of\ Repowring \times 0.97$$

- Conduct load flow studies to ensure the existing grid infrastructure can manage the increased output.
  - Evaluate the maximum, minimum, and average power flows under different conditions.
  - Identify voltage drops and power losses across the transmission network.
- Calculate the required conductor size for transmission lines based on

$$I = \frac{P}{\sqrt{3} \times V \times PF}$$

  - Ensure the conductor can manage the maximum current without overheating.
  - Maintain acceptable voltage levels at both ends of the line.
- Calculate the capacity of the step-up transformers at the substation.

$$Transfore\ Capacity\ (MVA) = \frac{Installed\ Capacity\ of\ Repowring}{PF}$$

- Validate the substation capacity to handle the new load.
  - Ensure breakers, switchgear, and busbars can accommodate the increased short-circuit currents.
  - Design protection systems to handle faults and overloads.

8 Logistical Considerations

Assessing the feasibility of transporting larger wind turbine components, such as blades and nacelles, to repowering sites requires a detailed evaluation of logistical challenges and infrastructure readiness. Modern wind turbines feature significantly larger blades, requiring precise measurement of blade dimensions, including their length and width, to plan transportation effectively. For instance, the increased size of these components necessitates specialized planning for routes and handling.

The existing road network forms a critical aspect of this assessment. Road width, curvature, and load-bearing capacity are key factors to determine whether current infrastructure can accommodate the size and weight of turbine components. Narrow or sharply curved roads may require upgrades or rerouting, while load restrictions could necessitate reinforcement of existing roadways or bridges.

Since some of the land required for widening these turns may fall within forest areas, it is necessary to apply for a land lease and obtain permission from the forest department for road widening. Acquiring the land lease may require approval from relevant authorities to ensure compliance with environmental standards and regulations.

Additionally, the availability of transportation equipment plays a significant role. Specialized vehicles, such as extendable trailers and high-capacity cranes, should be accessible to transport and install these components efficiently. Equipment limitations could significantly impact project timelines and costs.

The terrain and obstacles along the transportation route also warrant careful consideration. Steep slopes, tight turns, bridges, and other barriers may create logistical bottlenecks, necessitating terrain modification or the construction of bypasses. Mitigating such challenges is crucial to ensuring the smooth transport of components without compromising safety or environmental integrity.

A thorough logistical assessment incorporating these inputs may ensure the feasibility of repowering projects and streamline the process of transporting modern turbine components to site locations.

Every vehicle requires a certain amount of width when traveling on a straight path. However, on a curved path, the width requirement increases because the front and rear wheels follow different tracks while navigating the curve. This results in a reduction of the road's effective carrying capacity. Consequently, additional widening of the road becomes essential on curved sections to ensure the carrying capacity remains consistent throughout the curve.

- Mechanical widening is the additional road width required on curves due to the vehicle's wheelbase.

$$W_m = \frac{L^2}{2R}$$

where,

  - L - length of the vehicle
  - R - radius of the horizontal curve

- Psychological widening is entirely influenced by the design speed and the radius of the horizontal curve. It arises purely from psychological factors and is independent of the vehicle's wheelbase.

$$W_{psy} = \frac{V}{0.95\sqrt{R}}$$

where,

  - V - design speed

- The overall widening needed is the combination of psychological widening and mechanical widening.

$$W_{extra} = W_m + W_{psy}$$

To calculate the load-carrying capacity of a road for transporting heavy turbine blades, the road's structural capacity to withstand the combined weight of the blade and the transport vehicle is evaluated.

- Road's Bearing Capacity (CBR Method): The California Bearing Ratio (CBR) method is commonly used to estimate the road's load-carrying capacity:

$$P_{road} = 10.2\ x\ CBR$$

- Load Distribution on Axles: The total load applied by the vehicle is distributed across its axles:

$$F_a = \frac{W_{total}}{N_a}$$

where,

  - F_a - Load per axle (in tons)
  - W_{total} - Total weight of the vehicle + blade (in tons or kN)
  - N_a - Number of axles

- Tire Contact Pressure: The actual pressure exerted on the road surface by the tires is given by:

$$P_{tire} = \frac{F_a}{A}$$

where,

  - P_{tire} - Tire contact pressure (in tons)
  - W_{total} - Total weight of the vehicle + blade (in tons or kN)
  - A – Contact area (m^2)

- The load-carrying capacity of the road is acceptable if:

$$P_{tire} \leq P_{road}$$

If $P_{tire} \leq P_{road}$, the road is not strong enough and requires reinforcement.

9 Regulatory and Environmental Considerations

Regulatory and social compliance is a critical aspect of implementing repowering projects. These measures ensure that projects adhere to applicable laws and regulations, are socially acceptable, and minimize potential negative impacts on local communities and the environment.

9.1 Environmental Regulations and Permits

Repowering projects require several permits and regulatory clearances depending on their location, size, and scope. Common permits include environmental, land use, building, electrical, grid connection, planning, noise, and decommissioning permits. Below is a detailed breakdown of key requirements:

Environmental Permits

Environmental permits address issues such as water quality, wildlife protection, noise pollution, and air quality. The exact requirements vary depending on the location of the wind farm and local environmental laws. These permits often involve assessing and managing potential environmental impacts, including effects on wildlife, habitats, and protected areas. A key component is the EIA, which evaluates the project's potential environmental effects and outlines mitigation strategies.

Additional environmental permits may include:

- **Waste Management Permits**: To ensure the proper disposal of project-related waste, including non-recyclable materials.
- **Water Use Permits**: To prevent negative impacts on local water resources.
- **Land Use Licenses**: To confirm that the project does not encroach on sensitive areas like wetlands or protected ecosystems.

To ensure compliance, developers should work closely with local regulatory bodies.

Land Use Permits

Permits related to land use, such as zoning approvals, may be required to ensure compliance with local zoning laws and land-use regulations. Local authorities typically issue these permits.

Building Permits

Building permits are necessary for constructing new infrastructure, such as substations or transmission lines, as part of the repowering project. These permits ensure that all construction adheres to safety and building codes.

Electrical Permits

Electrical permits may be required for the installation and operation of electrical equipment like transformers and switchgear. These permits ensure compliance with technical and safety standards during the repowering process.

Central and State Government Permits

- **Central Government:** Permissions may be required if the project is located on central government land or funded by central government programs. Agencies such as the Department of Energy or Bureau of Land Management oversee these approvals.
- **State Government:** Depending on the state, specific permits may be required, such as licenses for RE generation or carbon emission compliance.

Grid Connection Permits

Before connecting the repowered wind farm to the electrical grid, a grid connection permit should be obtained from the relevant transmission or distribution operator (M. E. MERC 2024). The licensing process involves:

- Assessing the wind farm's impact on grid stability.
- Ensuring compliance with technical and safety requirements.

- Submitting analyses of the electrical infrastructure, grid protection measures, and stability studies.

Planning Permits

Planning permits verify compliance with regional planning laws and policies. Applications should include:

- Details of the project site.
- Specifications of proposed turbines.
- Results from environmental assessments.
- Plans to address community concerns and mitigation measures.

Noise Permits

Noise permits ensure that the project adheres to local noise regulations. This involves:

- Conducting noise assessments on the proposed turbines.
- Addressing potential impacts on the community and proposing mitigation strategies.

Decommissioning Permits

End-of-life permits ensure compliance with regulations governing the decommissioning and disposal of old turbines. Applications should include:

- A detailed plan for dismantling turbines and associated infrastructure.
- Proposals for the safe disposal and recycling of components, including blades.

Repowering projects should comply with the guidelines of the MNRE and state nodal agencies. Developers should collaborate closely with local, state, and central authorities to secure all necessary permits (WINDExchange 2024).

Prior to initiating a repowering project, the following approvals should be obtained from regulatory authorities:

- **Land Acquisition and Resettlement**: Repowering may require additional land, potentially displacing residents. Compliance with relevant laws is critical.
- **Building Codes and Safety Standards**: All structures and systems should adhere to applicable codes.
- **Grid Connection Rules**: Approval from grid authorities is necessary to maintain grid stability.
- **SIA**: Conducting an SIA helps identify potential social impacts and develop mitigation strategies.
- **Stakeholder Engagement**: Engaging with local communities, authorities, and organizations ensures social acceptance and minimizes adverse impacts.

9.2 Restrictions related to Western Ghats

In Maharashtra, several locations within the Western Ghats region were identified as ideal for wind farm development. These projects can impact wildlife sanctuaries, including tiger protection zones, forest boundaries, and world heritage sites. Numerous commercial proposals have been made to establish wind power projects in the Western Ghats, and several have already been completed. Unfortunately, the locations deemed ideal for wind farms are found along the crest lines of the Western Ghats, where high-speed winds are consistent. These areas also feature the steepest slopes, highly fragile ecosystems, and are accessed via biodiverse lateritic plateaus that host some of the most unique biodiversity in the region. Transporting massive construction cranes—of the kind used for constructing skyscrapers—and the large wind masts to these mountain crests necessitates building roads in these remote areas. This process results in extensive destruction of forests, habitats, and soils, often causing landslides and significant soil erosion in these high-rainfall zones.

The Western Ghats is a biodiversity hotspot spanning six states, 44 districts, and 142 talukas. It is home to 13 national parks and numerous wildlife sanctuaries, and UNESCO has recognized it as a global biodiversity hotspot. Many rivers that supply water to six major states originate in these ghats. Stretching 1,600 km from the Gujarat-Maharashtra border through Maharashtra, Goa, Karnataka, Kerala, and Tamil Nadu, the range ends at Kanyakumari. The Western Ghats hosts a rich variety of flora and fauna, including 7,500 species of flowering plants, 140 species of mammals, 500 species of birds, 180 species of amphibians, 6,000 species of insects, and 300 species of freshwater fish. Among these, approximately 330 globally threatened species are found within the region.

Recognizing the fragile ecological state of the Western Ghats, the Ministry of Environment and Forests, Government of India, established the Western Ghats Ecology Expert Panel (WGEEP) through an order dated March 4, 2010. The panel was assigned the following responsibilities:

- Assess the current ecological condition of the Western Ghats.
- Identify and demarcate ecologically sensitive areas within the region and recommend their notification as ecologically sensitive zones under the Environment Protection Act (EPA) of 1986.
- Propose measures for the conservation, protection, and rejuvenation of the Western Ghats, in consultation with the people and governments of the states within the Ghats.
- Suggest effective modalities for establishing the Western Ghats Ecology Authority under the EPA of 1986 to ensure sustainable development in the region.
- Address other relevant environmental and ecological issues concerning the Western Ghats.
- Additionally, as a subsequent directive, the ministry expanded the panel's mandate to include Ratnagiri and Sindhudurg districts, incorporating their coastal areas, and specifically examine the Gundia and Athirappilly hydroelectric projects. The panel was also tasked with providing recommendations regarding the moratorium on new mining licenses in Goa.

Given the diverse variations within the Western Ghats region, the committee developed a classification scale to determine ecological sensitivity under Sections 3 and 5(i) of the Environment Protection Rules, 1986. The classification includes:

- Ecologically Sensitive Zone 1 (ESZ1): Areas of highest ecological sensitivity.

- Ecologically Sensitive Zone 2 (ESZ2): Areas of high ecological sensitivity.
- Ecologically Sensitive Zone 3 (ESZ3): Areas of moderate ecological sensitivity.

To map the ecological sensitivity of the Western Ghats, the following criteria were considered:

- Biological Attributes: Including biodiversity richness, species rarity, habitat diversity, productivity, ecological or biological resilience, and cultural and historical significance.
- Geo-Climatic Attributes: Encompassing topographic features, climatic conditions, and hazard vulnerability.
- Stakeholder Valuation: Incorporating opinions from the public, local governing bodies, zilla panchayats, village-level political entities, and civil society organizations.

The report proposed designating approximately 65% of the Ghat region as ecologically sensitive zones (ESZ1 or ESZ2). Additionally, it recommended prohibiting the establishment of new thermal power plants and high-speed wind farms in the area (see Table 3). The report further advocated for a complete ban on converting public land to private ownership and on allocating forest land for non-forest activities within ESZ1 and ESZ2. The WGEEP has developed a set of broad guidelines for various sectors through extensive consultations with officials, experts, civil society groups, and the public. Below are the proposed guidelines and summary recommendations for the wind power sector:

Table 3: Proposed guidelines and summary recommendations for the wind power sector

Sector	ESZ1	ESZ2	ESZ3
Wind Power	Prohibit large-scale wind power projects	Allow regulated wind power projects only after cumulative assessments	Approve wind projects solely after conducting a comprehensive EIA (CEIA)

Repowering wind farms in India, particularly in ecologically sensitive areas like the Western Ghats, requires addressing critical environmental issues to ensure compliance with international conservation standards and local regulatory frameworks. Projects located near or within World Heritage Sites should cross-reference their potential impacts with global conservation standards, such as UNESCO's guidelines for preserving Outstanding Universal Value (OUV). An explicit protocol may be established to demonstrate compliance with these guidelines, ensuring that repowering activities do not compromise the ecological integrity of these sites. This includes conducting detailed EIAs that align with best international practices, such as the International Union for Conservation of Nature (IUCN) guidelines, and implementing mitigation measures to minimize habitat disruption, biodiversity loss, and landscape alteration.

The recommendations of the Gadgil Committee, which classified the Western Ghats into Ecologically Sensitive Zones (ESZs) based on their ecological significance, provide a critical framework for repowering projects. A detailed implementation plan should be developed to adhere to these recommendations, particularly in ESZ-1 (highly sensitive zones), where stringent restrictions on development activities apply. This includes avoiding repowering in areas with high biodiversity value, ensuring minimal forest clearance, and adopting low-impact technologies. Additionally, projects near wildlife sanctuaries or tiger protection zones should comply with the Wildlife Protection Act, 1972 and obtain clearances from the National Board for Wildlife (NBWL). A comprehensive environmental preservation strategy should be integrated into project design, incorporating measures such as habitat restoration, biodiversity conservation plans, and community engagement to ensure sustainable development. By aligning with global heritage conservation guidelines and local regulatory frameworks, repowering projects can achieve a balance between renewable energy goals and ecological preservation.

High-density wind farms in Maharashtra are located near the villages of Chalkewadi and Vankusawade in the Satara district, situated on a plateau atop the northern ranges of the Western Ghats. During the early stages of wind farm development, EIA studies were not mandatory. The plateau complex, where the wind farm is established, is primarily privately owned by local villagers and wind energy companies, with portions near the reservoir under the ownership of the State Forest Department. The wind energy companies purchase land from the local villagers to establish wind farms.

The development of wind farms represented an intensive intervention on the plateau landscape, involving activities such as road construction, excavation, and the use of cement-concrete for wind turbine foundations, poles, transformer rooms, and other infrastructure. Additional developments included guest houses, storage facilities for oil and chemicals, and the creation of level surfaces for cranes and heavy equipment. These activities have significantly impacted the ground and local habitat, resulting in the following:

- Intensified human settlement in the area,
- Decreased water storage areas in certain locations,
- Habitat fragmentation due to road construction, soil erosion and road-related wildlife mortality,
- Bird collisions with wind turbine blades and towers.

These developments highlighted the need for balancing repowering projects with ecological conservation in sensitive regions like the Western Ghats.

This Western Ghats is ecologically sensitive, and any development projects, including power generation, should adhere to strict environmental and conservation guidelines. While the Western Ghats have significant potential for renewable energy projects, particularly hydropower and wind energy, the declaration of this region as a World Heritage Site has introduced unique challenges for power generation projects.

Environmental Regulations and Restrictions

Western Ghats are subject to stringent environmental regulations to preserve their unique biodiversity. Projects should comply with the EIA Notification, 2006, and obtain clearances from the Ministry of Environment, Forest and Climate Change (MoEFCC). The UNESCO World Heritage status further complicates this process, as any project should demonstrate that it may not harm the ecological integrity of the region. For example, hydropower projects often face opposition due to their potential impact on river ecosystems, forest covers, and wildlife habitats.

Land Acquisition and Forest Clearances

Acquiring land for power generation projects in the Western Ghats is challenging due to the dense forest cover and protected areas. Projects require forest clearances under the Forest (Conservation) Act, 1980, which can be a lengthy and complex process. Additionally, the involvement of local communities and tribal populations, who often depend on forest resources, adds another layer of complexity. For instance, the Koyna Hydroelectric Project in Maharashtra, one of the largest hydropower projects in India, faced significant challenges in balancing energy generation with environmental and social concerns.

Biodiversity and Ecological Concerns

The Western Ghats are home to numerous endemic species and critical ecosystems. Power generation projects, especially hydropower and wind energy, can disrupt habitats, fragment forests, and affect migratory patterns of wildlife. For example, wind farms require large areas for turbine installation, which can lead to deforestation and habitat loss. Similarly, hydropower projects can alter river flow, affecting aquatic ecosystems and downstream communities.

Community Opposition and Social Challenges

Local communities and environmental activists often oppose power generation projects in the Western Ghats due to concerns about displacement, loss of livelihoods, and environmental degradation. For instance, the proposed Gundia Hydropower Project in Karnataka faced strong opposition from local communities and environmental groups, leading to its suspension. Such opposition can delay or even halt projects, increasing costs and uncertainty for developers.

Technical and Logistical Challenges

The rugged terrain of the Western Ghats poses significant technical and logistical challenges for power generation projects. Constructing infrastructure such as roads, transmission lines, and turbine foundations in hilly and forested areas is complex and costly. Additionally, the region's high rainfall and susceptibility to landslides further complicate construction and maintenance activities.

Maharashtra has several wind farms in the Western Ghats region, particularly in Satara and Sangli districts. These projects have faced challenges related to land acquisition, deforestation, and opposition from local communities.

9.3 Wildlife Permit or Clearance

The MoEFCC in India developed PARIVESH (Pro-Active and Responsive facilitation by Interactive, Virtuous, and Environmental Single-window Hub), an online platform designed to provide a single-window clearance system for various environmental, forest, and wildlife-related clearances for development projects (PARIVESH 2024).

Overview of PARIVESH's Wildlife Clearance Process:

- **Project Registration**: The process begins with registering as a user on the PARIVESH portal. The applicant should create an account and log in to access its services.
- **Submission of Project Details**: Once logged in, the applicant provides project details, including its objectives, location, and scope. If the project is likely to impact wildlife or their habitats, this should be explicitly stated during submission.
- **Screening by Authorities**: The submitted project details are reviewed by the relevant authorities to determine whether wildlife clearance is required. Projects with potential impacts on wildlife or habitats receive closer scrutiny.
- **Application for Wildlife Clearance**: If the screening process identifies the need for wildlife clearance, the applicant should formally apply by submitting all required documents, including detailed project reports and an assessment of its potential impact on wildlife and their habitats.
- **Document Submission**: The applicant uploads all relevant documents, including wildlife survey reports, EIA reports, and proposed mitigation measures, to the portal.
- **Review by the Expert Appraisal Committee (EAC)**: The EAC on Wildlife Conservation established by MoEFCC and comprising wildlife and conservation experts, reviews the application and supporting materials. The committee evaluates the proposed mitigation strategies and potential wildlife impacts.
- **Public Consultation** (If required): For large-scale or ecologically sensitive projects, public consultation may be mandated. During this process, stakeholders can share their opinions on the project's environmental and wildlife-related impacts.

- **Decision**: Based on the EAC's recommendations and feedback from public consultation (if applicable), MoEFCC decides whether to approve or reject the wildlife clearance. The applicant is notified of the decision through the PARIVESH portal.
- **Compliance and Monitoring**: Approved projects should comply with the conditions and mitigation measures specified by the authorities. Regular monitoring may be conducted to ensure adherence to wildlife conservation requirements.

This streamlined approach facilitates transparency and accountability in the clearance process while ensuring that wildlife conservation remains a priority in developmental activities.

9.4 Forest Clearance

The submitted project details are reviewed by the relevant authorities to determine whether forest clearance is required. Projects that may impact forested areas undergo more detailed scrutiny. Forest clearance is categorized based on the project's size and nature, including:

- Category A: Projects requiring approval from the MoEFCC Forest Advisory Committee (FAC) and the NBWL.
- Category B: Projects requiring approval from the State Board for Wildlife and the State Forest Department.
- Category C: Projects within the notified boundaries of towns or cities, or linear projects (e.g., highways, transmission lines) in non-forest areas.

Overview of PARIVESH's Forest Clearance Process:

- **Application for Forest Clearance**: If the screening process determines that forest clearance is necessary, the applicant should apply for the appropriate category via the PARIVESH portal. The application should include all required documents, detailed project reports, and an assessment of the potential impact on forested areas.
- **Document Submission**: Applicants should upload all relevant studies, reports, and documents related to the project's potential forest impacts. This may include:
    - EIA Report

   - Forest Diversion Proposal (FDP)
   - Other supporting documentation as needed.
- **Review by Expert Committee**: The review process varies based on the project category:
   - Category A Projects: Assessed by the NBWL and the FAC.
   - Category B Projects: Evaluated by the State Board for Wildlife and the State Forest Department.
- **Public Consultation**: For Category A projects, a public consultation is required. This process allows stakeholders to provide feedback on the potential impacts of the project on forests and wildlife.
- **Decision**: The MoEFCC or the State Forest Department makes the final decision on forest clearance based on recommendations from the expert committees and feedback from public consultations (if applicable). The decision is communicated to the applicant through the PARIVESH portal.
- **Compliance and Monitoring**: Approved projects should adhere to the conditions and mitigation measures specified by the authorities. Regular monitoring ensures compliance with forest conservation requirements.

10 Case Study for Chalkewadi

10.1 Wind Repowering Feasibility Study

This section proposes repowering the Chalkewadi site in Satara, Maharashtra, by introducing turbines with different capacities. This wind farm was originally commissioned in 1996. The old wind farm, which had a capacity of 2 MW comprised of 8 BHEL-NORDEX make WTGs each rated at 250 kW, has been repowered. Additional shadow analysis and micro-siting studies have been conducted to demonstrate the maximized utilization of resources and space available at this site.

Turbines from five manufacturers, each with a capacity exceeding 1 MW and without any significant operational issues, have been considered for repowering optimization. The selection of these WTGs was conducted in accordance with the MNRE guidelines, specifically choosing models included in the Revised List of Models and Manufacturers (RLMM) after the declaration of the new procedure on 1st November 2018.

Table 4: WTGs selected for repowering optimization

Model Type	Power (MW)	Voltage (V)	Rotor Diameter (m)	Hub Height (m)
SUZLON S120 DFIG 2.1 MW (50 Hz)	2.1	690	120	120
S133 2.6 MW/ 2.8 MW / 3.0 MW	2.6	690	133	140
SG 3.6-145 (LM 71.0 P2)	3.6	690	145	127.5
AGW 147/4.2	4.2	925	147	120
MWL-160-5.2MW with rotor blade LM78.3P, hub height 120m	5.2	950	160	120

Based on these parameters, the developed optimization program proposed in Chapter 6 generated an optimal solution for the technical, economic, and power evacuation. The optimization program considering all input parameters and optimization constraints found the optimal status of repowering is to use one WTG model named MWL-160-5.2MW.

10.1.1 *Technical Analysis*

The installed capacity of the repowered wind farm increased significantly from 2 MW to 5.2 MW, while the number of turbines was reduced from 8 to just one. This optimization resulted in a fourfold increase in annual energy generation, reaching 13,665.6 MWh. The cost of energy for the repowered plant was calculated at 1,761.12 ₹/MWh, which is lower than standard market rates, ensuring cost competitiveness. Additionally, the repowering capacity ratio and renewable energy yield ratio were determined to be 2.6 and 3.9, respectively, highlighting the improved efficiency and performance of the repowered plant. The comparison between the old and repowered wind farms at Chalkewadi highlights significant advancements in technology and efficiency. (see Table 5).

Table 5: Comparison of old and repowered wind farms

Wind Farm	Old Wind Farm	Repowered Wind Fram	Changes
Chalkewadi	Generators: 8 * 250 kW Hub height: 50 m Rotor diameter: 29.7 m	Generators: 1 * 5.2 MW Hub height: 120 m Rotor diameter: 160 m	Reduced number of WTGs while increasing installed capacity by 2.6, along with extending the rotor diameter and hub height to 130 m and 70 m, respectively.

Table 6: Optimization results for technical and economical solutions of the repowered wind farm

Status		**Optimal**
Number of Turbines		**1**
Installed Capacity (MW)		**5.2**
Annual Energy Generation (MWh)		**13665.6**
Area Occupied (Hectare)		**38.4**
PVC (INR)	**₹**	**466,893,859.58**
PVB(INR)	**₹**	**636,174,033.22**
NPV (INR)	**₹**	**169,280,173.64**
PU Cost of Energy (INR/MWh)	**₹**	**1,761.12**
IRR (%)		**11.89%**
Payback Period (Years)		**6.62**
Repowering Capacity Ratio		**2.6**
Renewable Energy Yield Ratio		**3.9**

10.1.2 Financial Analysis

The economic viability of the repowered wind farm was analyzed using an 8.56% discount rate (WACC) and a 20-year project lifespan. The PVC was calculated at ₹46.6 crore, while the PVB amounted to ₹63.6 crore, resulting in a NPV of ₹16.9 crore. The IRR was calculated at 11.89%, demonstrating robust profitability, with a payback period of just 6.62 years, further underscoring the financial feasibility of the project. The optimization results for technical and economic analyses are summarized as follows:

10.1.3 Logistical Analysis

Road widening and strengthening

The blade length of the MWL-160-5.2MW WTG model is 78.6 meters. As no WTGs with similar blade lengths currently exist in the area, careful feasibility of transportation is required to determine the need for road widening or strengthening at specific locations to facilitate the transportation of these blades. The road from Satara to Chalkewadi has been identified for a widening and strengthening study, as depicted in Figure 8 using Google Maps.

Figure 8: Satara-Chalkewadi Road

Based on the modeling presented in Chapter 8, the extent of the required road modifications based on the below listed assumption can be determined as follows:

- $L = 90\ m$ - specialized trailer length + blade segment
- $R = 20\ m$ - radius of the horizontal curve (assuming sharp curves in hilly roads from Satara-Chalkewadi).
- $V = 20\ km/h\,(5.56\ m/s)$ - design speed (realistic for oversized loads on hilly and narrow roads).
- California Bearing Ratio = 6% (rural roads in hilly area of Satara-Chalkewadi).
- $W_{total} = 120\ tons$ - Total weight of the vehicle + segment of blade (in tons or kN)
- $N_a = 16$ - Number of axles (specialized heavy-load trailers)
- $A = 0.3\ m^2$ – Contact area of tire of vehicle (m^2) (heavy-load tires)

Determining the need for additional widening of the road and load-carrying capacity of a road for transporting heavy turbine blades yields:

- Mechanical widening ($W_m = 202.5\ cm$)
- Psychological widening $\left(W_{psy} \approx 4.71\ cm\right)$
- The overall widening ($W_{extra} = 207.21\ cm$)

The road should be widened by approximately 207 cm (2.07 meters) on curves to safely transport the blade.

- Road's Bearing Capacity ($P_{road} = 61.2\ \ tons/m^2$)
- Load Distribution on Axles ($F_a = 7.5\ tons/axle$)
- Tire Contact Pressure ($P_{tire} = 25\ \ tons/m^2$)
- The load-carrying capacity of the road is:

$$(P_{tire} = 25\ \ tons/m^2) \geq (P_{road} = 61.2\ \ tons/m^2)$$

Since $P_{tire} \leq P_{road}$ (25 ≤ 61.2), the road's load-carrying capacity is sufficient for transporting the blade. However, if the WTG manufacturer provides segmented blades, the need for additional road widening and strengthening can be avoided.

Decommissioning Costs

The decommissioning cost analysis is for illustrative purposes only and should not be considered a benchmark. In this scenario, an annual escalation rate of 3% is assumed for decommissioning-related costs. Decommissioning is projected to begin in the 15th year and conclude at the end of the WTGs' useful life (20 years). The analysis accounts for the following costs in the 15th year: ₹15 lakhs for dismantling, ₹3 lakhs for site clearance, and ₹1.5 lakhs for blade disposal. Thereafter, the escalation rate may be applied to these costs each subsequent year. Additionally, an annual income of ₹4 lakhs from the sale of scrap material is included in the calculations.

Table 7: Evaluation of cost of decommissioning

Cost		15^{th} Yr	16^{th} Yr	17^{th} Yr	18^{th} Yr	19^{th} Yr	20^{th} Yr	Total
Dismentling (₹ Lakhs)	DS	15.00	15.45	15.91	16.39	16.88	17.39	97.03
Site Clearing (₹ Lakhs)	SC	3.00	3.09	3.19	3.29	3.39	3.49	19.45
Blade Disposal (₹ Lakhs)	DB	1.50	1.55	1.59	1.64	1.69	1.75	9.73
Scrap Material (₹ Lakhs)	SM	4.00	4.00	4.00	4.00	4.00	4.00	24.00
Dicommissioning cost (₹ Lakhs)	DS+SC+DM-SM	12.50	13.01	13.54	14.08	14.64	15.21	**102.21**

As shown in Table 7, the cost of dismantling each 250-kW wind turbine includes the removal of the nacelle, tower, rotor, and hub. Due to the smaller size of these turbines, the dismantling cost is estimated at ₹97.03 lakhs. Site clearance, which involves the removal of foundations, cables, and other non-reusable infrastructure, is estimated at ₹19.45 lakhs, reflecting the smaller foundation size. Blade disposal, including transportation and fees for landfill or incineration, is estimated at ₹9.73 lakhs. The income from the sale of scrap materials is estimated at ₹4 lakhs annually, partially offsetting the cost. The total decommissioning cost is calculated to be ₹102.21 lakhs.

Additionally, waste management costs for recycling and proper disposal of decommissioned turbine components are estimated ₹10 lakh, depending on the material composition and recycling feasibility. Site restoration, including soil remediation and revegetation, is expected to cost ₹5 lakh to ensure environmental compliance and land usability for future projects. Moreover, regulatory compliance expenses, covering permits, clearances, and required reporting, are estimated at ₹2 lakh. These costs, while necessary, contribute to responsible decommissioning and sustainable land management.

Considering all these factors, the total decommissioning cost for the entire repowering project amounts to ₹1.19 crore, encompassing site clearance, blade disposal, waste management, site restoration, and regulatory compliance. While these costs represent a necessary investment in responsible decommissioning, they are partially offset by the income from scrap material sales, reducing the overall financial burden. Proper planning and execution of the decommissioning process ensure environmental sustainability and regulatory adherence, paving the way for efficient repowering and enhanced wind energy generation.

Table 8: Optimization results for electrical and power evacuation solutions of the repowered wind farm

Power Evacuation (MW)	**5.044**
Foundation Size (m2)	**327.00**
Foundation Side (m)	**18.08**
Foundation Radius (m)	**10.20**
Cable Length (m)	**484.00**
LV Cable Size (mm2)	**1105.86**
MV Cable Size (mm2)	**14.93**
HV Cable Size (mm2)	**5.60**
Transformer Size (MVA)	**5.47**
Circuit Breaker Size (kA)	**5.20**
Busbar Size (mm2)	**37.41**

10.1.4 Electrical and Power Evacuation Analysis

The power evacuation efficiency is estimated at 97%, with 3% attributed to losses. Consequently, the repowered wind farm evacuates 5.044 MW of power and 1.66 MVar of reactive power to the grid. The cable length from the turbine to the transformer measures 484 meters, with optimized cable sizes determined as 1106 mm² for LV, 15 mm² for MV, and 5.6 mm² for HV. The transformer is rated at 5.47 MVA, while the circuit breaker has a current-carrying capacity of 5.2 kA. The busbar size is calculated as 37.41 mm². For the tower's foundation, an area of 327 m² is required. Depending on the chosen foundation type, the radius for a circular foundation is 10.2 meters, while the side length for a square foundation is 18 meters. These optimized parameters ensure efficient and reliable integration of the repowered wind farm into the grid, as summarized above.

To leverage the utilization of the existing power evacuation infrastructure, the Chalkewadi WF should be equipped with a transformer rated at 0.95/11 kV (±2% voltage tolerance) with a power capacity of 5.5 MVA. For enhanced reliability, an alternative configuration comprising two transformers, each rated at 0.95/11 kV (±2% tolerance) with a power capacity of 2.75 MVA, can be considered. This approach enhances the system's reliability and ensures continuous power supply in the event of failure or maintenance of one transformer.

The Chalkewadi Circuit No. I substation has a connecting load capacity of 15 MW. The current load distribution across this substation is as follows:

- MEDA: 8 × 250 kW = 2 MW
- NEPC: 2 × 225 kW = 0.45 MW
- Wind Power: 8 × 600 kW = 4.8 MW
- SEP: (2 × 500 kW) + (4 × 225 kW) = 1.9 MW
- Vestas: 225 kW
- Total Connected Load: 9.15 MW

Following the repowering of the existing 2 MW MEDA wind turbine to 5.2 MW, an additional 3.2 MW needs to be accommodated in the power evacuation system. The new total load would be 12.35 MW. This remains within the 15 MW capacity of the substation. The existing power evacuation accommodates the additional load without exceeding the substation's power evacuation capacity. No immediate upgrades to the existing evacuation infrastructure are necessary in this configuration.

The double-circuit power evacuation route originates from the Chalkewadi Wind Farm (0.95/11 kV) and extends through the Chalkewadi Circuit No. I Substation (33/11 kV). From there, it traverses approximately 20 km to the MSEDCL Parli Substation (33/11 kV), followed by an additional 16 km stretch through the MSEDCL Shendre Substation (33/11 kV). The pathway converges at its point of interaction (POI), the MSEDCL Satara MIDC EHV Substation (220/33 kV), facilitating the integration of power into the regional transmission network. The wind farm layout is illustrated in Figure 9.

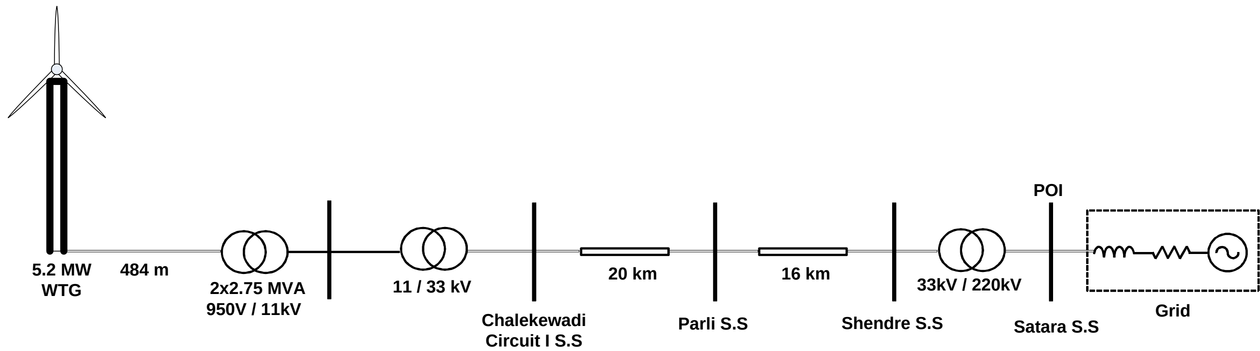

Figure 9: Wind Farm Layout

10.1.5 Sensitivity Analysis

For the following cases, a sensitivity analysis is done.

- 5–10% decrease/increase in Capacity Factor
- 5–10% decrease/increase in Feed-in Tarriff
- 5–10% decrease/increase in COPEX
- 5–10% decrease/increase in OPEX
- 5–10% decrease/increase in WACC

The sensitivity variables have been assessed by increasing and decreasing them by 5% and 10%, respectively, to analyze the system's response to different variables. The purpose of sensitivity analysis is to evaluate how uncertain input variables influence the system's performance and economic viability. Each parameter is examined independently, and its effects are analyzed separately, as outlined below.

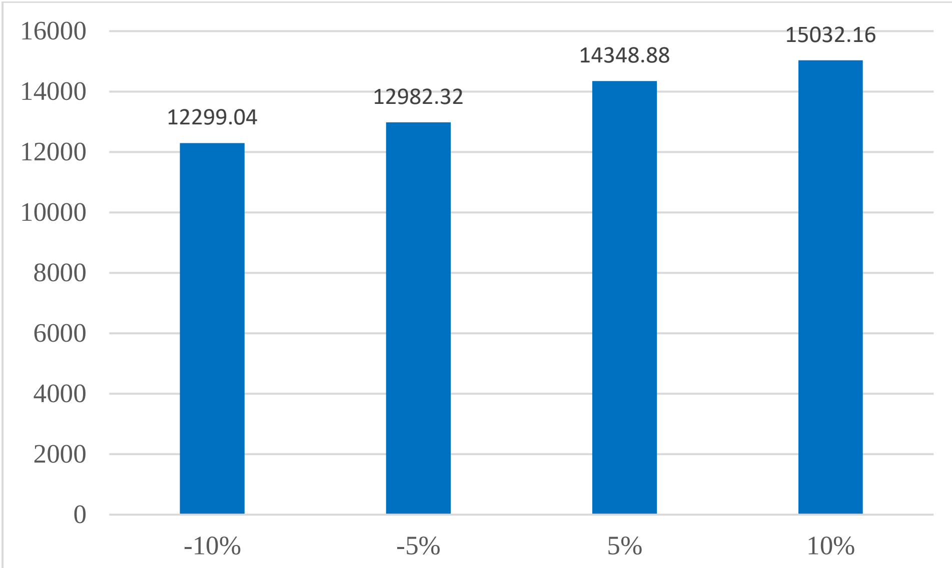

Figure 10: Annual energy generation sensitivity to variations in capacity factors

The repowered plant's annual energy generation is directly influenced by the capacity factor, meaning that as the capacity factor increases, energy generation rises, and vice versa. Figure 10 illustrates the sensitivity of annual energy generation to variations in the capacity factor. A 10% decrease in the capacity factor leads to a reduction in annual energy generation to 10,122.99 MWh, whereas a 10% increase boosts energy generation to 15,032.16 MWh. These variations highlight the crucial role of the capacity factor in determining the overall energy output of the plant.

For the sensitivity analysis, five key parameters are considered: capacity factor, feed-in tariff, COPEX, OPEX, and WACC. Table 9 presents the sensitivity of IRR to variations in these input parameters. The degree of sensitivity can be classified into two main categories. The first category includes capacity factor, feed-in tariff, and WACC, which have a significant impact on IRR. Specifically, a reduction in capacity factor or feed-in tariff leads to a decline in IRR. A 10% decrease in these parameters causes the IRR to drop to 10.10% and 10.11%, respectively. The second category consists of COPEX and OPEX. A 10% increase in COPEX results in the IRR decreasing to 10.28%. Despite these variations, the overall economic feasibility of implementing a wind energy grid at this location remains favorable.

Table 9: IRR sensitivity to changes in input parameters

Sensitive input parameters	IRR (%)

	-10%	-5%	+5%	+10%
Capacity Factor	10.10	11.01	12.75	13.58
Feed-in Tariff	10.11	11.02	12.75	13.58
COPEX	13.76	12.80	11.06	10.28
OPEX	12.21	12.06	11.74	11.58
WACC	11.87	11.88	11.91	11.92

Table 10 presents the sensitivity analysis of the payback period in response to variations in five key input parameters. Like the IRR sensitivity analysis, the degree of sensitivity can be categorized into two main groups. The first category includes capacity factor, feed-in tariff, and COPEX, which have a significant impact on the payback period. A 10% reduction in either capacity factor or feed-in tariff extends the payback period to 7.55 years, whereas a 10% decrease in COPEX shortens it to 5.83 years. Conversely, a 10% increase in capacity factor or feed-in tariff reduces the payback period to 5.9 years, while a 10% increase in COPEX prolongs it to 7.45 years. The second category consists of OPEX and WACC, which have a moderate to minimal effect on the payback period. Overall, these findings emphasize the critical influence of capacity factor, feed-in tariff, and COPEX in determining the financial viability and payback period of the repowering project.

Table 10: Payback sensitivity to changes in input parameters

Sensitive input parameters	Payback Period (years)			
	-10%	-5%	+5%	+10%
Capacity Factor	7.55	7.06	6.24	5.90
Feed-in Tariff	7.55	7.05	6.24	5.90
COPEX	5.83	6.22	7.03	7.45
OPEX	6.49	6.55	6.69	6.76
WACC	6.63	6.63	6.61	6.61

Error! Reference source not found. presents the sensitivity analysis of NPV in response to variations in five key input parameters. Among these, capacity factor, feed-in tariff, COPEX, and WACC have a significant impact on NPV, while OPEX has a moderate effect. A 10% reduction in capacity factor or feed-in tariff lowers NPV to ₹10.6 crore, whereas a 10% decrease in COPEX or WACC results in a substantial increase, raising NPV to ₹21.6 crore and ₹20.4 crore, respectively. Conversely, a 10% increase in capacity factor or feed-in tariff boosts NPV to ₹23.3 crore, while a 10% rise in COPEX or WACC reduces the NPV to ₹12.2 crore and ₹13.8 crore, respectively. Additionally, a 10% increase or decrease in OPEX leads to an NPV variation, increasing it to ₹ 18 crore or decreasing it to ₹15.9 crore.

Table 11: NPV sensitivity to changes in input parameters

Sensitive input parameters	NPV (₹ crore)			
	-10%	-5%	+5%	+10%
Capacity Factor	10.6	13.7	20.1	23.3
Feed-in Tariff	10.6	13.8	20.1	23.3
COPEX	21.6	19.3	14.6	12.2
OPEX	18.0	17.4	16.4	15.9
WACC	20.4	18.7	15.3	13.8

Table 12 presents the sensitivity analysis of the p.u cost of energy in response to variations in five key input parameters. The degree of sensitivity can be categorized into two main groups. The first category includes capacity factor and COPEX, which have a significant impact on the p.u cost of energy. A 10% reduction in capacity factor results in the highest p.u cost of ₹1,956.59/MWh, whereas a 10% decrease in COPEX leads to the lowest p.u cost of ₹1,584.57/MWh. Conversely, a 10% increase in capacity factor reduces the p.u cost to ₹1,601.01/MWh, while a 10% increase in COPEX raises it to ₹1,936.70/MWh. The second category consists of OPEX and WACC, which have a moderate effect on the p.u cost of energy. A 10% reduction in OPEX lowers the p.u cost to ₹1,721.95/MWh, while a 10% decrease in WACC increases it to ₹1,789.85/MWh. In contrast, a 10% increase in OPEX raises the p.u cost to ₹1,799.33/MWh, whereas a 10% increase in WACC lowers it to ₹1,734.26/MWh. Notably, feed-in tariff variations have no impact on the p.u cost of energy.

Table 12: P.u. cost of energy sensitivity to changes in input parameters

Sensitive input parameters	P.u. Cost of Energy (₹ / MWh)			
	-10%	-5%	+5%	+10%
Capacity Factor	1,956.59	1,853.81	1,677.25	1,601.01
Feed-in Tariff	1,760.64	1,760.64	1,760.64	1,760.64
COPEX	1,584.57	1,672.61	1,848.67	1,936.70
OPEX	1,721.95	1,741.29	1,779.98	1,799.33
WACC	1,789.85	1,774.87	1,747.12	1,734.26

10.1.6 Tariff Analysis

The analysis in the previous sections was based on a fixed feed-in tariff with a zero-escalation scheme. This tariff structure ensures stable cash flow throughout the project's lifespan while mitigating the risk of buyer default, as savings relative to the grid tariff are expected to grow over time. Alternatively, a fixed feed-in tariff with a predetermined escalation rate—currently the most widely adopted tariff model—is also examined. Under this scheme, developers offer an initially lower fixed tariff with an annual escalation rate, typically ranging from 1 - 4%, making it more appealing to buyers from the outset. For this analysis, the initial fixed feed-in tariff is set at ₹4,000 per MWh as the baseline assumption. The tariff structure is outlined in Table 13.

Table 13: Proposed tariff structure scenarios

Scenarios	Traiff Structure
Scenario 1	Fixed feed-in tariff with zero escalation scheme
Scenario 2	Fixed feed-in tariff with a 2% annual escalation for the first 10 years, followed by a fixed tariff equal to the 10th-year rate for the remaining lifespan
Scenario 3	Fixed feed-in tariff with a 4% annual escalation for the first 10 years, followed by a fixed tariff equal to the 10th-year rate for the remaining lifespan
Scenario 4	Fixed feed-in tariff with a 2% annual escalation throughout the lifespan
Scenario 5	Fixed feed-in tariff with a 4% annual escalation throughout the lifespan

The comparative analysis of tariff structure scenarios, as presented in Table 14, highlights the financial implications of different escalation strategies on the project's viability. Scenario 1, which follows a fixed feed-in tariff with zero escalation, offers one of the most attractive investment options in terms of NPV at ₹16.93 crore, a relatively high IRR of 11.89%, and the shortest payback period of 6.62 years. This structure ensures stable cash flow and mitigates buyer default risk; however, it does not account for tariff escalation.

On the other hand, Scenario 2, which includes a 2% annual escalation for the first 10 years followed by a fixed tariff, performs the weakest financially, with the lowest NPV (₹9.03 crore) and IRR (9.90%), coupled with the longest payback period of 8.02 years. The limited escalation period results in slower revenue growth, making this structure less attractive to investors. Scenario 3, which applies to a higher 4% annual escalation for the first 10 years, improves financial performance significantly, with an NPV of ₹15.59 crore, IRR of 11.55%, and a payback period of 7.43 years, showing that a higher initial escalation rate positively impacts early cash flows and overall returns.

Table 14: Comparative analysis of tariff structure scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
NPV (₹ crore)	16.93	9.03	15.59	10.89	20.28
IRR (%)	11.89	9.90	11.55	10.35	12.42
Payback Period (years)	6.62	8.02	7.43	8.02	7.43

When considering escalation throughout the lifespan, Scenario 4, with a 2% annual escalation for the entire project duration, achieves an NPV of ₹10.89 crore and an IRR of 10.35%, making it slightly better than Scenario 2 but still less financially rewarding. The payback period remains at 8.02 years, indicating slow capital recovery. In contrast, Scenario 5, with a 4% annual escalation throughout the lifespan, emerges as the most financially viable option, yielding the highest NPV of ₹20.28 crore, the strongest IRR of 12.42%, and a reasonable payback period of 7.43 years. The continuous escalation ensures growing revenue over time, making this structure the most attractive for long-term investment.

Overall, the analysis suggests that while fixed tariff structures offer stability and quick payback, escalation-based tariffs—especially those with a 4% annual increase throughout the lifespan—

provide superior long-term financial returns, making them the preferred choice for investors seeking sustainable profitability.

10.2 Hybrid Wind-Storage Feasibility Study

Ensuring dispatchable and available 24/7 RE is essential for a reliable and resilient power system. Energy Storage Systems (ESS) play a pivotal role in achieving this by storing excess energy generated from RE sources and making it available when solar or wind generation is insufficient. To mitigate the variability and intermittency associated with wind energy, ESS are integrated with wind power. Additionally, ESS helps mitigate RE variability, enhance grid stability, enable energy, and peak load shifting, provide ancillary services, and support greater RE integration into the grid, improving overall system efficiency and reliability.

The deviation between the scheduled and actual energy generation within each time block is referred to as the absolute error. This error can be expressed as a percentage using the following formula:

$$Absolute\ Error\ (\%) = \frac{P_{AC} - P_{SCH}}{AvC}$$

Where,

P_{AC}: Actual Generation is the electricity produced and supplied to the grid by a generator, as recorded by the interface meters.

P_{SCH}: Scheduled Generation is the total planned capacity of wind turbines, solar inverters, or solar thermal generators capable of generating power during a specific time block.

AvC: Available Capacity is combined capacity of wind turbines, solar inverters, or solar thermal generators that are operational and capable of generating power during a specific time block.

For the sale or self-consumption of power within Maharashtra, if the actual generation injected by a stand-alone generator or the aggregate generation at a pooling substation differs from the scheduled generation, the QCA shall be responsible for paying the deviation charge for the excess or shortfall to the State DSM Pool through the SLDC, as outlined in **Error! Not a valid bookmark self-reference.**.

Table 15: Deviation Charge for under- or over-injection, for sale or self-consumption of power within Maharashtra *(MERC 2018)*

S. No.	Absolute Error in %age terms in 15-minute time block	Deviation Charge payable to State DSM Pool
1	≤ 10%	None
2	> 10% but ≤ 20%	At Rs. 0.50 per unit.
3	> 20% but ≤ 30%	At Rs. 0.50 per unit for the shortfall or excess beyond 10% and up to 20% + Rs. 1.00 per unit for the balance energy beyond 20% and up to 30%.
4	> 30%	At Rs. 0.50 per unit for the shortfall or excess beyond 10% and up to 20% + Rs. 1.00 per unit for the shortfall or excess beyond 20% and up to 30% + Rs. 1.50 per unit for the balance energy beyond 30%.

Table 16: Comparative assessment of battery technologies.

Parameter	Lithium-Ion	Flow Batteries	Sodium-Sulfur
Energy Density (Wh/kg)	210-325	10-50	150-240
Round-Trip Efficiency	90-95%	70-85%	75-90%
Cycle Life (cycles)	5,000-10,000	10,000+	2,500-4,500
Reaction Time	Sub second to seconds	Sub second	Sub second
Discharge Duration (hours)	4-6	6+	4-6
Operating Temperature (°C)	-20 - 60	5 - 45	300-350
Cost (₹ crore/MWh)	1.3 - 2.6	2.6 – 5.2	2.2 – 3.5
Lifespan (years)	10-15	20+	10-15
Safety	Moderate (thermal runaway risk)	High (non-flammable electrolytes)	Low (high-temperature operation)
Applications	Short- to medium-duration storage, frequency regulation	Long-duration storage, renewable integration	Grid-scale storage, renewable integration

10.2.1 Battery Technologies

For a 11.2 MWh ESS connected to a 5.2 MW WTG, the most suitable battery technologies include Lithium-Ion (Li-ion), Flow Batteries, and Sodium-Sulfur (NaS) batteries. Each technology has unique characteristics that make it suitable for grid-scale energy storage applications. Table 16 presents the comparative assessment of battery technologies.

For the wind-storage hybrid, the Li-ion batteries are the most suitable choice due to their high efficiency, declining costs, and proven performance in grid-scale applications. However, if the project requires long-duration storage or frequent cycling, Flow Batteries could be a viable alternative despite their higher upfront costs. NaS batteries are less recommended due to their high operating temperatures and safety concerns, although they remain an option for large-scale grid storage.

10.2.2 Battery Size Design

The purpose of the battery storage system dictates its required size, including power rating and energy capacity. One important function is arbitrage, where the battery stores energy when electricity prices are low and discharges when prices are high, maximizing financial returns. Another application is energy shifting, allowing excess energy generated during high wind periods to be stored and later used during low wind periods, improving grid stability. Additionally, battery storage plays a crucial role in frequency regulation by providing a fast response to grid fluctuations, enhancing system reliability. It can also serve as a backup power source, ensuring a continuous electricity supply to grid during generation outages. Proper sizing of the battery system is essential to effectively meet the demands of each application.

As stated in section 10.1.1, the annual energy production of the repowered wind farm is calculated to be 13,665.6 MWh using the following equation:

$$E_{WF} = P_{rated} \times CF \times 8760$$

The daily energy production can be estimated as:

$$E_{daily} = \frac{E_{WF}}{365} = 37.4\ MWh$$

Of the wind farm's daily energy production, 70% is directly supplied to the grid, while the remaining 30% is allocated for charging the ESS.

$$E_{BESS} = 30\% \times E_{daily} = 11.2\ MWh$$

The required E_{BESS} is 11.2 MWh. The ESS power rating of the battery for a 4-hour arbitrage cycle, where excess wind power is stored and discharged during peak price hours is found as:

$$P_{BESS} = \frac{E_{BESS}}{T_{storage}}$$

Based on this, the required P_{BESS} is 2.8 MW. The usable energy capacity is determined by accounting for the round-trip efficiency (η) and depth of discharge (DoD). Assuming $\eta_{BESS} = 90\%$ and $DoD = 90\%$ for lithium-ion batteries, the effective available energy is calculated according:

$$E_{usable} = E_{BESS} \times \eta_{BESS} \times DoD$$

The usable energy capacity is 9.07 MWh. The inverter must be sized to match the battery's discharge power. The appropriate inverter capacity is determined based on the following criteria:

$$P_{inv} = \frac{P_{BESS}}{\eta_{inv}}$$

Assuming $\eta_{inv} = 95\%$, the required inverter P_{inv} is 2.95 MW. An inverter with a power rating of at least 3 MW should be used to ensure it can accommodate the maximum power output of the battery system.

The inverter's efficiency directly impacts the usable energy output of the battery system. The actual energy delivered to the grid can be calculated as:

$$E_{Grid} = E_{usable} \times \eta_{inv}$$

The revised useable energy delivered to grid E_{Grid} is 8.62 MWh.

10.2.3 Cost Benefit Breakdown

The ESS can be used for arbitrage services to capitalize on electricity price fluctuations by storing energy during periods of low demand (and lower prices) and discharging it during peak demand when prices are higher. The cost of Li-ion batteries for the wind-storage hybrid system is estimated at ₹1.5 crore per MWh, the annual O&M cost is ₹150 per kWh, and the inverter cost is ₹4000 per kW.

$$C_{bat} = E_{BESS} \times ₹1.5 \frac{crore}{MWh} = ₹16.8\ crore$$

$$C_{O\&M} = P_{BESS} \times 1000 \times ₹150/kWh \times 15\ years = ₹0.63\ crore$$

$$C_{inv} = P_{inv} \times 1000 \times ₹4000/kW = ₹1.2\ crore$$

The total cost over 15 years can be found as:

$$TOC = C_{bat} + C_{O\&M} + C_{inv} = ₹18.63\ crore$$

Assuming the ESS charges during off-peak hours when electricity prices are low (₹3/kWh) and discharges during peak hours when prices rise to ₹6/kWh. Consequently, the energy arbitrage revenue is determined as follows:

$$R = E_{Grid} \times 1000 \times ₹3/kWh = ₹\ 25{,}860/cycle$$

Lithium-ion batteries typically support 3,000 to 6,000 cycles at 90% DoD. However, their capacity and performance gradually degrade over time, reducing the number of effective cycles. In practical applications, an ESS can complete approximately 300 to 500 cycles per year, considering periods when the battery is not fully cycled due to lower price differentials or maintenance requirements. Based on these assumptions, the annual revenue from arbitrage services is calculated as follows:

$$R_{annual} = ₹\ 25{,}860/cycle \times 300\ cycle/year = ₹\ 77.58\ lakhs/year$$

The payback period would be:

$$Payback\ Period = \frac{₹18.63\ crore}{₹\ 77.58\ lakhs/year} \approx 24\ years$$

From a financial perspective, integrating a 11.2 MWh ESS with a 5.2 MW WF is not economically viable. This analysis does not take battery degradation into account. Incorporating battery degradation would likely result in a longer payback period and a lower return on investment. The high capital cost the ESS resulted in a poor return on investment and an extended payback period beyond its lifespan.

10.2.4 VGF Analysis

VGF is increasingly being made available for energy storage projects in India. Under these schemes, up to 40% of the capital cost of ESS projects can be covered through government grants, reducing the financial burden on developers. This funding aims to improve the economic feasibility of battery storage systems by lowering upfront investment costs, thereby enhancing the adoption of wind-storage hybrid systems.

With a 40% VGF grant, the effective capital cost of 11.2 MWh ESS is recalculated as:

$$New\ Capital\ Cost = ESS\ Cost - (VGF\ Percentage * \ ESS\ Cost)$$

$$New\ Capital\ Cost = 18.63 - (40\% * 18.63) = ₹11.18\ crore$$

The revised payback period can now be determined as:

$$Revised\ Payback\ Period = \frac{New\ Capital\ Cost}{Annual\ Ravenue}$$

$$Revised\ Payback\ Period = \frac{₹11.18\ crore}{₹\ 77.58\ lakhs/year} \approx 14.4\ years$$

By incorporating 40% VGF, the capital cost of the 11.2 MWh ESS is reduced to ₹11.18 crore, significantly improving the financial viability of the project. The payback period decreases from 24 years to approximately 14.4 years, making the investment barely attractive to developers and investors. This highlights the critical role of government incentives in accelerating energy storage adoption, enhancing grid stability, and ensuring the successful integration of RE.

10.3 Hybrid Wind-Solar Feasibility Study

The shadow free area for the repowered wind farm with 5.2 MW capacity WTG, was estimated via shadow analysis as illustrated in Figure 11. In the analysis, the white areas show the shadows cast by the wind turbine, while the remaining areas are shadow-free. A solar power plant is planned to be installed in these shadow-free zones. The total area of the plant is 44.38 hectares, with the shadow-free area measuring 40.5 hectares. It is assumed that 12 m^2 are required to generate 1 kW of solar power. Based on this, the installed solar capacity in the shadow-free area is calculated to be 33.75 MW. Considering a CUF of 20% for solar, this equates to an annual energy generation of approximately 59.13 GWh. Therefore, the hybrid plant may have a total installed capacity of 38.95 MW, and it is expected to generate 72.795 GWh of electricity annually. Consequently, the hybrid plant achieves a repowering capacity ratio of 19.475 and a renewable energy yield ratio of 20.8.

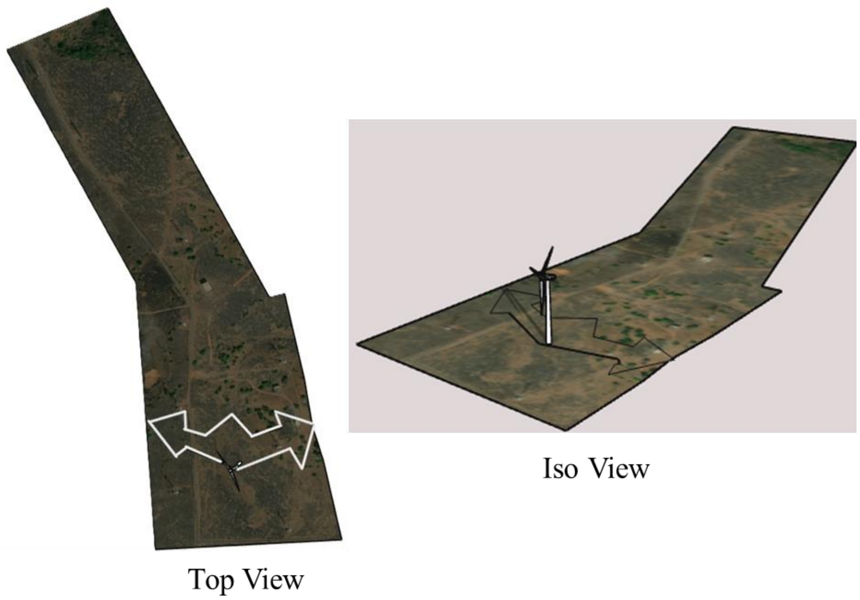

Figure 11: Shadow view of 5.2 MW GTG

10.3.1 Solar Farm Layout

The solar plant layout, designed with a total capacity of 33.75 MW, incorporates modules listed in the MNRE's Approved List of Models and Manufacturers (ALMM) for Solar PV modules. The selected module, NSM500-132, has a rated capacity of 500 Wp, ensuring compliance with regulatory standards and delivering reliable performance for the project. The open circuit voltage for the module is 45.27 V DC, and the system employs 4.4 MVA inverters with maximum operation DC voltage of 1500 V. The plant configuration consists of 33 modules per string, with a total of 67500 modules strategically arranged to maximize energy generation while minimizing shading. The layout includes 8 inverters, each handling approximately 4.4 MVA, distributed across the plant for optimized cable routing and minimal transmission losses. Pathways are incorporated to ensure easy maintenance access, and adequate spacing is provided between rows to prevent shading and allow for efficient cleaning. A central substation is found to aggregate power from all inverters and feed it into the grid, ensuring seamless energy evacuation.

Table 17: Hybrid system summarized

Total Area Occupied (Hectare)	**44.38**
Shadow-free Area (Hectare)	**40.5**
Total Installed Capacity (MW)	**38.95**
Total Annual Energy Generation (GWh)	**72.795**
Repowering Capacity Ratio	**19.475**
Renewable Energy Yield Ratio	**20.8**

This design reflects the step-by-step determination of the plant topology and aligns with the assumptions provided, delivering a robust and efficient solar PV system.

- Total Number of PV Modules

The total number of modules needed for a 33.75 MW installed capacity is:

$$Total\ Number\ of\ Modules = \frac{Installed\ Capacity}{PV\ Module\ Capacity} = \frac{33.75\ MW}{500\ Wp} = \mathbf{67,500\ modules}$$

67,500 modules of 500Wp capacity are needed to build a solar farm with a total capacity of 33.75 MW.

- Number of Inverters

$$Total\ Number\ of\ Inverters = \frac{Installed\ Capacity}{Inverter\ Capacity} = \frac{33.75\ MW}{4.4\ MVA} = 7.67$$

Thus, 8 inverters are required.

- String Design

For an inverter with a 1500V DC input and a 500 Wp module with an open-circuit voltage of 45.27V DC:

- Modules per string:

$$Modules\ per\ String = \frac{String\ Voltage}{Module\ V_{OC}} = \frac{1500}{45.27} = 33.13\ modules/string$$

These rounds to 33 modules per string.

- Strings per Inverter

$$String\ per\ Inverter = \frac{Inverter\ Capacity}{Panel\ Capacity \times Panels\ per\ String} = \frac{4.4\ MVA}{500\ Wp \times 33}$$
$$= 266.67\ strings$$

Thus, 266 strings are connected to each inverter.

10.3.2 Cost Benefit Breakdown

The financial assessment of a 33.75 MW solar farm utilizing 67,500 modules of 500Wp (NSM500-132) and 8 high-capacity inverters considers capital expenditures, operational costs, energy generation, and revenue streams.

The cost of high-efficiency solar modules is estimated at ₹15,000 per unit, leading to a total module cost of ₹101.25 crore. For power conversion, the project employs 8 inverters, each rated at 4.4 MVA, with a per-unit cost of ₹2.5 crore, summing up to ₹20 crore.

The Balance of System (BoS), which includes mounting structures, cabling, transformers, and other necessary components, typically accounts for 20-25% of the total module and inverter costs. In this case, the BoS cost is estimated at ₹24.25 crore.

The land requirement for the project, based on shadow-free area calculations, is 40.5 hectares (100 acres). With an assumed land acquisition cost of ₹10 lakh per acre, the total land cost amounts to ₹10 crore. Additional infrastructure expenses, including fencing, roads, and facilities, are projected at ₹5 crore.

Summing up these components, the total capital investment for the 33.75 MW solar farm stands at ₹160.5 crore. This comprehensive cost breakdown provides a foundation for assessing the project's financial viability and return on investment.

The annual O&M cost for the solar farm is typically 1-2% of the total capital cost. Assuming 1.5%, the estimated annual O&M cost is ₹2.4 crore. The solar farm is projected to generate 59,130 MWh per year and based on prevailing solar PPAs in India, the feed-in tariff is assumed to be ₹3.50/kWh. This results in an annual revenue of ₹20.7 crore, leading to a net annual revenue of ₹18.3 crore. Consequently, the estimated payback period for the project is approximately 8.7 years.

The NPV of the project is calculated based on an 8% discount rate over a 25-year project lifespan. Using standard NPV calculations, the project is estimated to have an NPV of ₹34.7 crore. Furthermore, the IRR for the solar farm is determined to be 11.5%, indicating strong financial viability and investment potential.

$$NPV = \sum_{t=1}^{T} \frac{Net\ Annual\ Revenue}{(1 - r_{DR})^t} - Total\ Capital\ Investment$$

11 Recommendations and Way Forward

- Mandatory Dismantling of Old Wind Turbines: Mandatory dismantling of old wind turbines that have exceeded their design life, accompanied by adequate financial incentives to facilitate the transition to repowered infrastructure.
- Promoting Investment Opportunities: Highlight the potential of repowering projects as a significant investment opportunity, ensuring adequate returns over the lifetime of repowered turbines (approximately 20 years) while enhancing the efficiency and capacity of wind power generation.

Recommendations for fragmented ownership:

- Allocate stakes in the new repowering project to current turbine owners based on their equity contribution, adjusted according to the valuation of their existing projects.
- For current owners who do not wish to invest further but want to remain part of the new project, offer stakes in the new project based on the value of dismantled assets and lost revenue.
- For owners who do not want to participate in the new project, provide a full buyout of their turbines and land rights, following standard valuation methods.

Recommendations for Enhancing Power Infrastructure and Renewable Integration:

- Strengthen Power Evacuation Infrastructure: Enhance power evacuation systems to prevent large-scale curtailment of generated power, a critical challenge for the RE sector. This may maximize the utilization of available power and improve grid reliability.
- Adopt a Futuristic Approach to Repowering: Integrate repowering with emerging technologies such as solar and ESSs. This hybrid approach may accelerate the adoption of renewables by offering greater flexibility and convenience for utilities.
- Deliver Cleaner and Predictable Energy: Enable power producers to supply secure, cleaner energy by aligning generation with demand patterns. This may improve energy predictability and make RE more viable for utilities and consumers alike.
- PPA Extensions and Termination Flexibility:

- Introduce provisions in PPAs to disallow multiple extensions beyond the standard operational life of 20 years.
- Disallow continued operation of outdated turbines and encouraged repowering by offering efficient PPA termination processes without penalties.

- Incentives for Repowered Projects:
    - Enhance repowering incentives by relaxing criteria, such as the requirement for replaced turbines to have at least 1.5 times the original capacity. This flexibility may address financial constraints and encourage higher adoption rates.
    - Provide generation-based incentives for repowered wind farms that exceed predefined performance benchmarks, such as increased energy output. These performance-linked rewards may motivate wind farm owners to optimize their operations.
- Financial Support Mechanisms:
    - Loan Guarantees: Introduce government-backed loan guarantees to lower lender risk, enabling reduced interest rates and longer repayment periods for repowering projects. This can help bridge financing gaps.
    - Feed-in Tariffs: Establish long-term feed-in tariffs for repowered projects to provide stable revenue streams during the initial operational period, mitigating risks of revenue shortfalls and enhancing project bankability.
- Power Banking and Infrastructure Upgrades:
    - Extend the power banking period for repowered projects to accommodate fluctuations in power generation and grid demand, ensuring smooth integration into the grid.
    - Upgrade substation capacities and components, including evacuation voltage levels and transmission infrastructure, to support the increased power capacity from repowered turbines.
- Long-Term Policy Roadmap:

  - Develop a comprehensive, long-term policy for repowering that includes strategies for investment, the design of large-scale wind turbines, and the improvement of supporting infrastructure.
  - Undertake a large-scale augmentation of transmission facilities to handle increased energy output and ensure efficient power evacuation.
- Address Regulatory Barriers:
  - Revise micro-siting regulations to allow for greater flexibility in hub height and rotor diameter adjustments. This may ensure efficient land use while maintaining safety distances between turbines and homes.
- Promote Hybridization of Wind and Solar Projects:
  - Leverage the complementary generation patterns of wind and solar energy to maximize overall energy production throughout the day and season. Wind power is typically stronger during night-time and early morning hours, while solar power peaks at midday, ensuring a balanced supply and reduced reliance on fossil fuels.
  - Utilize existing wind farm infrastructure for co-located solar installations, reducing the need for additional land acquisition and minimizing project development costs.
- Land Use Optimization:
  - Encourage hybrid projects to make efficient use of existing wind farmland, promoting responsible land use while reducing costs associated with acquiring new land for solar and wind installations.

To ensure sustainable development in the Western Ghats, the following mitigation measures are recommended for wind projects:

- All repowering projects proposed in the Western Ghats should pass the regulatory and environmental permits set to protect the region. This assessment should evaluate the combined environmental, ecological, and social impacts of the project alongside existing and proposed developments in the region.
- When land is acquired for wind power development in societal or ecologically sensitive areas of the Western Ghats, a benefit-sharing arrangement should be mandated. This could

include financial compensation to local communities or groups based on the amount of power generated on their land, ensuring equitable distribution of the project's benefits.

By implementing these recommendations, the repowering policy may not only encourage the transition to more efficient wind turbine technologies but also unlock new investment opportunities, improve energy production, and ensure the long-term sustainability of renewable energy in Maharashtra.

12 Conclusion

This report has been prepared in compliance with all relevant standards, regulations, and industrial practices, acknowledging that repowering wind farms is an emerging concept. The MNRE is actively promoting repowering to increase RE integration in India. In this study, the best repowering solution was achieved by developing an optimization algorithm that maximizes the energy production of WTGs.

The report incorporates three case studies: a standalone wind case, wind-storage hybrid, and a wind/solar hybrid case for the Chalkewadi site, found in Satara, Maharashtra. Five different rated WTGs available in the RLMM were selected for repowering analysis. Shadow analysis and micro-siting analysis were conducted using SketchUp, Google Earth, and standard measurements specified by MNRE.

For this specific site, the study results show that optimal status of repowering can be achieved with a turbine of 5.2 MW capacity and the installation of a solar farm with a capacity of 33.75 MW. The annual energy yield is projected to be 72.795 GWh. Consequently, the hybrid plant achieves a repowering capacity ratio of 19.475 and a renewable energy yield ratio of 20.8. The analysis proves that by employing hybrid generation, the plant's capacity increases substantially while optimizing the use of space and resources. Therefore, a hybrid generation system is highly recommended for this site.

In conclusion, the repowering of old wind turbines in India indicates that existing wind project developers are unlikely to pursue repowering initiatives independently in the future unless key technical, regulatory, and commercial challenges are effectively addressed. Even when owners show interest, several significant hurdles remain, including the complexities of multiple ownership of WTGs at a single wind farm site, continuation of existing PPAs, the reluctance of utilities to support repowering through concessional wheeling and banking arrangements, and the need for substantial additional investments in power evacuation infrastructure. These issues create significant barriers to the successful initiation and implementation of repowering projects.

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