Confederation of Indian Industry

BEST PRACTICES FOR GROUND MOUNTED SOLAR AND WIND PLANTS

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This publication serves as a repository of best practices and operational insights for solar ground-mounted and wind power plants, intended for use by plant personnel involved in project development, operations, asset management, and sustainability initiatives. The content has been compiled from various credible sources, including data shared through industry participation in CII initiatives, CII Performance Excellence awards for Solar, Wind and Hybrid plants.

While due diligence has been exercised to capture representative benchmarks and industry leading practices, there may be additional high-performing projects or innovations that were not captured at the time of publication.

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FOREWORD

India stands at a critical juncture in its energy transition journey. As the country moves decisively toward a low-carbon future, renewable energy (RE) has emerged not only as an environmental imperative but also as an economic and strategic opportunity. With ambitious national targets and a dynamic policy landscape, the adoption of clean energy solutions—particularly ground mounted solar and wind—across states and sectors is gaining unprecedented momentum.

The pathway to accelerated RE deployment demands clarity, consistency, and confidence in both policy and execution frameworks. In this context, this publication on Best Practices for Ground Mounted Solar and Wind Plants offers timely and practical insights to support high-quality and sustainable project implementation. Drawing from successful case studies, technical standards, and real-world industry experience, the publication presents proven strategies to enhance project efficiency, reduce costs, and mitigate risks across the lifecycle—from planning and design to construction and operations.

It also highlights critical considerations such as land optimization, grid integration, environmental safeguards, and maintenance protocols that are essential for scaling up deployment without compromising long term performance. While the compilation is grounded in secondary research and field practices, it has been strengthened by the review and feedback of subject-matter experts, whose perspectives lend practical relevance to the content. I am confident that this publication will serve as a valuable reference for developers, EPC agencies, policymakers, investors, and energy professionals committed to accelerating India's clean energy goals. As we collectively pursue a more sustainable and resilient energy future, the adoption of standardized best practices will play a pivotal role in ensuring quality, reliability, and scalability across renewable energy projects.

Mr Ramesh Kymal

Chairman, Renewable Energy Council, CII-Godrej GBC

Acknowledgment

CII–Sohrabji Godrej Green Business Centre extends its sincere appreciation to all stakeholders from the renewable energy sector who participated in the **CII Performance Excellence Awards for Solar, Wind, Hybrid and Module Manufacturing Plants.** We are deeply grateful for their continued support and for sharing their best practices, backed by data, which have greatly enriched this initiative. We would also like to acknowledge the valuable cooperation and support provided by all participating organizations in sharing their technological advancements and case studies from operational renewable energy plants. Their contributions have been instrumental in shaping the insights presented in this publication. A special note of thanks is extended to **Dr. P. Jayakumar** (Chairman, CII Performance Excellence Awards 2026), **Mr. Sharad Saxena** (Jury Member, CII Performance Excellence Awards 2026), **Mr. A S Karanth** (Jury Member, CII Performance Excellence Awards 2026), **Dr S Gomathinayagam** (Jury Member, CII Performance Excellence Awards 2026), for generously sharing their time, expertise, and valuable inputs in the development of this publication. Their guidance has been pivotal to the success of this initiative.

EXECUTIVE SUMMARY

Executive Summary

A comprehensive benchmarking assessment of utility-scale solar PV and wind power plants across India has been carried out using the previous editions of *CII Performance Excellence Awards* datasets representing diverse climatic zones, technology configurations, resource regimes, and plant vintages. The study evaluates key performance indicators including capacity utilization factor (CUF), specific yield, plant availability, irradiation levels, wind power density (WPD), hub height, and regional operating conditions to establish national and state-level performance benchmarks for renewable energy assets.

Solar PV Plant Performance Benchmarking

The analysis of solar PV plants indicates that the **national average solar CUF** stabilizes at approximately **18.5%** [1], with best-in-class utility-scale plants in Rajasthan, Andhra Pradesh, and Madhya Pradesh achieving CUF levels of 24–26%. These high-performing plants are supported by superior solar irradiation levels (GHI of 2,100–2,300 kWh/m²), advanced module technologies, large plant capacities, tracker-based systems, innovations and best practices resulting in specific yields exceeding 2,200 MWh/MWp in certain cases.

The **national average specific yield** was observed at approximately **1,650 MWh/MWp** with an average plant availability of 98.9%, reflecting the maturity of India's solar O&M ecosystem. However, significant regional variation exists, with lower CUF values of 14–16% observed in regions such as Delhi, Maharashtra, and aging Tamil Nadu assets due to lower irradiation, high ambient temperatures, cloud cover, humidity effects, and plant degradation.

State-level solar performance across India is heavily dictated by regional Global Horizontal Irradiance (GHI) profiles, seasonal cloud cover, and geographic positioning, though operational standards remain consistently high nationwide. High-radiation zones like **Rajasthan** (GHI of 2,100–2,300 kWh/m²) and **Madhya Pradesh** lead the sector, both achieving top-tier CUFs reaching up to 26% and specific yields exceeding 2,270 MWh/MWp. **Andhra Pradesh** and **Telangana** also showcase exceptional performance bands, with best-in-class CUFs touching 25% and 24% respectively.

Regions with more volatile or lower resource regimes see reduced yields; for instance, **Tamil Nadu** and **Kerala** experience moderate performance ceilings with best-in-class CUFs capping at 18% and 17% due to localized cloud cover and monsoon.

Table 1: State Level performance Benchmarking for utility scale solar plants [2]

State	Average GHI (kWh/m²)	Average Plant Availability	Average CUF	Average Specific Yield (MWh/MWp)	Best-in-Class CUF
Rajasthan	2,100–2,300	99.7%	19–26%	1,700–2,270	26%
Gujarat	2,000–2,200	99.6%	19–21%	1,650–1,800	21%
Andhra Pradesh	1,850–2,050	99.9%	18–25%	1,600–2,260	26%
Karnataka	1,500–2,300	99.9%	15–21%	1,280–1,815	21%
Tamil Nadu	1,600–2,000	99.5%	15–18%	1,370–1,600	18%
Telangana	1,600–1,950	99.7%	14–24%	1,300–2,135	24%

State	Average GHI (kWh/m²)	Average Plant Availability	Average CUF	Average Specific Yield (MWh/MWp)	Best-in-Class CUF
Madhya Pradesh	1,500–2,000	99.9%	18–26%	1,560–2,289	26%
Maharashtra	1,500–2,000	99.9%	14–22%	1,250–1,980	23%
Kerala	1,600–2,000	99.9%	15–17%	1,380–1,490	17%
West Bengal	1,600	99.6%	15%	1,347	15%
New Delhi	1,300	99.9%	14%	1,250	14%

Wind Power Plant Performance Benchmarking

The wind power benchmarking study demonstrates a **national average CUF of approximately 27.97%** [3], with modern wind farms in **Gujarat and Karnataka** achieving best-in-class CUF levels of 34–37%. The national average plant availability of 98.18% indicates strong operational reliability and standardized maintenance practices across the sector.

The benchmarking exercise confirms that while geographical asset placement (site quality) provides a baseline, the deployment of modern turbine technology with optimized hub heights is critical to maximizing energy generation. Addressing regional grid integration and curtailment challenges will be vital to unlocking the full generation potential of lagging regions.

State-Level Performance & Regional Variations

Table 2: State Level performance Benchmarking for utility scale wind plants [4]

State	Total Capacity (MW)	Average Age (Years)	Average Hub Height (m)	Average Wind Power Density (W/m²)	Average Plant Availability	Average CUF	Best-in-Class CUF
Gujarat	911	6.1	129.8	248.1	99%	33%	37%
Karnataka	489	8.2	105.7	252.2	98%	29%	35%
Madhya Pradesh	479	6.3	113.3	302.4	98%	28%	30%
Tamil Nadu	290	13.4	90.8	217.6	98%	27%	35%
Andhra Pradesh	844	7.3	106.1	259.5	98%	27%	33%
Maharashtra	312	9.8	102.2	216.6	99%	26%	36%
Rajasthan	267	14	93	223.0	98%	20%	24%

Regional performance deviations have been identified. **Rajasthan** records comparatively lower CUF values of 20% due to seasonal wind variability and grid curtailment during peak renewable generation periods. **Tamil Nadu**, despite having older assets with lower hub heights, continues to maintain competitive performance with average CUF of 27% due to historically superior site selection and favourable wind corridors established during the early stages of India's wind sector development.

Evaluating the performance of utility-scale, ground mounted solar and wind power plants require looking beyond resource availability alone. While Global Horizontal Irradiation (GHI), Direct Normal Irradiation (DNI), and average wind speeds remain fundamental indicators, plants operating under similar weather conditions often demonstrate significant differences in Capacity Utilisation Factor (CUF), Performance Ratio (PR), availability, and financial returns.

These variations arise from a combination of **asset technology and operational practices.** The following analysis highlights the key factors contributing to these performance differences.

1. Asset Technology and Engineering Design
2. Operation and Maintenance (O&M) Strategy
3. Asset age and Policy Environment

1. Asset Technology and Engineering Design

Technology selection and engineering decisions established during project development create the baseline for long-term plant performance.

Ground-Mounted Solar PV Plants

- **DC-to-AC Ratio (Inverter Loading Ratio – ILR):** Plants designed with higher ILRs can capture additional energy during morning and evening periods. However, higher ratios may also increase clipping losses during peak irradiance conditions.

- **Tracking Technology:** Single-axis tracking systems can significantly enhance energy generation compared with fixed-tilt installations. Advanced tracking algorithms further optimise tracker positioning by minimising row-to-row shading and improving energy capture throughout the day.

- **Bifacial Modules and Ground Reflectivity:** Bifacial modules utilise albedo effect from the ground surface. Plants located on high-reflectivity terrain, such as desert sand or gravel, can achieve higher energy yields compared with installations on darker surfaces or dense vegetation.

Wind Power Plants

- **Hub Height and Rotor Diameter:** Modern turbines equipped with larger rotor diameters and taller hub heights access stronger and more consistent wind resources, resulting in superior energy generation compared with earlier turbine designs.

- **Wake Losses and Micro-Siting:** Turbine placement plays a critical role in plant efficiency. Poor layout optimisation can lead to wake interactions, where upstream turbines reduce the available wind energy for downstream machines. Terrain complexity further influences airflow quality and turbine performance

2. Operation and Maintenance (O&M) Strategy

- **Wake Losses and Micro-Siting:** Turbine placement plays a critical role in plant efficiency. Poor layout optimisation can lead to wake interactions, where upstream turbines reduce the available wind energy for downstream machines. Terrain complexity further influences airflow quality and turbine performance

2. Operation and Maintenance (O&M) Strategy

The effectiveness of O&M practices throughout the asset lifecycle can create substantial performance differences, even among identical plants.

Strategic versus Reactive Maintenance

- **Component Reliability and Spare Management:** Failures of critical components such as inverters, gearboxes, or major turbine assemblies can lead to extended outages. Plants employing predictive maintenance techniques, including thermal inspections, drone-based assessments, and vibration monitoring, are better positioned to prevent catastrophic failures and minimise downtime.

- **Supply Chain and Logistics:** Access to skilled technicians and spare parts significantly influences restoration timelines. Plants located within established renewable energy clusters often benefit from stronger service ecosystems, whereas remote facilities may experience prolonged outages due to logistical constraints.

3. Asset Age and Policy Environment

The commissioning period and prevailing policy framework also influence renewable plant performance.

- **Technology Vintage:** Plants commissioned in earlier phases of renewable deployment were built using technologies and design philosophies that differ significantly from those available today. Advancements in modules, inverters, turbines, controls, and monitoring systems enable newer assets to achieve higher levels of performance.

- **Repowering and Regulatory Support:** Policy initiatives promoting asset repowering allow older facilities to improve performance through selective upgrades, such as blade replacements, nacelle retrofits, or modern control systems, resulting in enhanced energy generation and operational efficiency.

The performance of utility-scale solar and wind power plants is therefore shaped by a complex interplay of technology choices, environmental conditions, operational excellence, and asset maturity. Understanding these factors enables developers and operators to identify improvement opportunities, optimise plant performance, and maximise long-term value creation from renewable energy assets.

Abbreviations

BD	Break Down
CERC	Central Electricity Regulatory Commission
CUF	Capacity Utilization Factor
EL	Electroluminescence
EPC	Engineering, Procurement, and Construction
GMS	Ground Mounted Solar
GW	Gigawatts
HT	High Tension
IGBT	Insulated Gate Bipolar Transistors
kl	Kilo Liters
kWh	Kilo Watt Hour
MNRE	Ministry of New and Renewable Energy
MWp	Mega Watt Peak
OEM	Original Equipment Manufacturer
PID	Potential Induced Degradation
SCB	String Combiner Boxes
SCADA	Supervisory Control and Data Acquisition
SVG	Static VAR Generator
WTG	Wind Turbine Generator

Introduction

The global transition towards clean energy has entered a decisive phase in 2026, with countries accelerating efforts to decarbonize their power sectors in line with climate commitments. In India, this transition is being driven by a strong policy and regulatory framework led by the Ministry of New and Renewable Energy (MNRE), the Central Electricity Regulatory Commission (CERC), and other allied institutions. Ensuring the efficient development, operation, and maintenance of ground mounted solar and wind power plants is therefore critical to achieving national targets while maintaining grid stability, reliability, and cost competitiveness.

This *Best Practice Manual for Ground Mounted Solar and Wind Plants* has been developed as a comprehensive reference document for developers, EPC agencies, O&M service providers, asset managers, and other stakeholders across the renewable energy value chain. The manual aligns with prevailing regulatory frameworks, technical standards, and policy directives, and aims to promote uniformity, quality assurance, and performance optimization across utility-scale renewable energy projects.

As of 31st March 2026, India's total installed power generation capacity has exceeded approximately **530 GW** [5], with renewable energy capacity reaching around **274 GW** [6], representing a substantial share of the overall energy mix. Solar energy contributes **150 GW** [7], while wind energy accounts for over **56 GW** [8] of installed capacity. The total non-fossil fuel-based capacity has crossed approximately **283 GW** [9], reflecting sustained progress towards national climate goals.

This manual consolidates industry best practices. It provides structured guidance across all phases of the project lifecycle—from resource assessment and site selection to design optimization, engineering, procurement, construction, commissioning, and advanced operations including digital monitoring and predictive maintenance.

By adopting the practices outlined in this manual, stakeholders can enhance plant efficiency, operational reliability, minimize operational risks, and improve overall project bankability.

Objective of the Publication

The primary objective of this publication is to develop a structured and comprehensive repository of best practices for ground mounted solar and wind power plants, derived from insights and learnings of high-performing renewable energy plants recognized under the *CII Performance Excellence Awards for Solar, Wind, Hybrid and Module Manufacturing Plants.*

This manual aims to capture, standardize, and disseminate proven practices across the renewable energy value chain, enabling stakeholders to enhance operational efficiency, and achieve superior plant performance. The specific objectives are as follows:

- To identify and document industry-leading practices in the design, engineering, construction, operation, and maintenance of utility-scale solar and wind power plants.
- To establish standardized benchmarks and performance frameworks aligned with national policies, regulatory requirements, and global best practices.
- To facilitate knowledge sharing across developers, EPC agencies, OEMs, and O&M service providers by leveraging learnings from award-winning organizations.
- To promote continuous improvement, innovation, and adoption of advanced technologies, including digital monitoring, analytics, and predictive maintenance.
- To enhance plant reliability, optimize energy yield, reduce lifecycle costs, and improve overall asset performance.
- To support the sector in achieving higher levels of safety, sustainability, and operational excellence in line with India’s renewable energy targets.

Through this publication, CII seeks to create a robust knowledge platform that not only recognizes excellence but also enables its replication across the industry, thereby contributing to the development of a resilient, efficient, and future-ready renewable energy ecosystem.

GROUND MOUNTED SOLAR

Brief Scenario of Ground Mounted Solar in India

Ground mounted solar power projects constitute the backbone of India's renewable energy expansion, driven by their scalability, cost competitiveness, and ease of integration with the national grid. As of March 2026, utility-scale solar installations account for the majority share of the country's total solar capacity, with large solar parks and open access projects playing a pivotal role in accelerating deployment.

India has achieved significant growth in ground-mounted solar capacity, crossing approximately **150 GW** [10] **of installed solar power**, supported by robust policy interventions from the Ministry of New and Renewable Energy and regulatory frameworks guided by the Central Electricity Regulatory Commission. Key initiatives such as solar park schemes, competitive tariff-based bidding, and transmission infrastructure development under the Green Energy Corridor have enabled rapid capacity addition across states like Rajasthan, Gujarat, and Karnataka.

This has been complemented by advancements in module efficiency (including bifacial modules and tracker-based systems), improved plant design, and digital monitoring solutions that enhance performance and reliability.

Ground mounted solar projects are also benefiting from evolving market mechanisms such as green open access, corporate power purchase agreements (PPAs), and hybrid projects integrating wind and energy storage systems. These developments are improving grid stability and enabling round-the-clock renewable power supply.

However, the sector continues to face challenges related to land acquisition, transmission connectivity, intermittency management, and regulatory uncertainties across states. Addressing these challenges through streamlined policies, improved grid infrastructure, and adoption of energy storage solutions will be critical for sustaining growth.

Overall, ground mounted solar in India is on a strong growth trajectory and is expected to remain a key contributor towards achieving the national target of **500 GW** [11] **of non-fossil fuel capacity by 2030**, and to achieve 60% [12] cumulative electric power installed capacity from non-fossil fuel-based energy resources by 2035 reinforcing India's position as a global leader in renewable energy deployment.

Table 3: Performance parameter of utility scale solar ground mounted plants [13]

Sl.No.	Plant	State/UT	Capacity	Age of Plant	Actual GHI	CUF	Specific Yield	Plant Availability
			MWp	Years	kWh/m^2	%	MWh/MWp	%
1	Plant-1	Telangana	Up to 20 MWp	9	1,096	15.13%	1,325	99.65%
2	Plant-2	Kerala		2	2,022	17.05%	1,493	99.97%
3	Plant-3	Tamil Nadu		3	1,932	17.77%	1,556	99.99%
4	Plant-4	New Delhi		8	1,331	14.07%	1,232	99.91%
5	Plant-5	Karnataka		7	1,945	18.78%	1,646	99.94%
6	Plant-6	Uttar Pradesh		2	1,990	16.77%	1,469	99.50%
7	Plant-7	Tamil Nadu		3	1,980	16.34%	1,431	99.02%
8	Plant-8	West Bengal		3	1,620	15.37%	1,347	99.60%
9	Plant-9	Telangana		7	1,683	14.88%	1,304	99.80%
10	Plant-10	Telangana		3	1,901	16.78%	1,470	99.50%
11	Plant-11	Rajasthan		2	1,858	16.32%	1,430	99.93%
12	Plant-12	Tamil Nadu		2	2,008	18.25%	1,599	99.59%
13	Plant-13	Rajasthan		4	1,773	15.17%	1,329	100.00%
14	Plant-14	Tamil Nadu		2	1,647	15.80%	1,384	98.00%
15	Plant-15	Andhra Pradesh		4	1,859	16.85%	1,476	99.99%
16	Plant-16	Tamil Nadu		3	1,650	17.13%	1,500	99.06%
17	Plant-17	Odisha		1	1,756	16.70%	1,463	82.19%
18	Plant-18	Maharashtra		1	1,568	14.31%	1,254	99.98%
19	Plant-19	Karnataka		6	1,522	14.64%	1,282	100.00%
20	Plant-20	Telangana		9	1,850	18.38%	1,610	99.76%
21	Plant-21	Andhra Pradesh		6	1,838	16.60%	1,454	100.00%
22	Plant-22	Tamil Nadu		4	1,936	17.74%	1,554	99.68%

Sl.No.	Plant	State/UT	Capacity	Age of Plant	Actual GHI	CUF	Specific Yield	Plant Availability
			MWp	Years	kWh/m²	%	MWh/MWp	%
23	Plant-23	Karnataka	20 MWp to 50 MWp	7	1,769	19.17%	1,679	99.80%
24	Plant-24	Karnataka		7	2,300	20.72%	1,815	100.00%
25	Plant-25	Telangana		7	1,944	24.37%	2,135	99.65%
26	Plant-26	Andhra Pradesh		6	2,003	18.74%	1,642	99.99%
27	Plant-27	Maharashtra		6	2,001	22.69%	1,987	99.98%
28	Plant-28	Andhra Pradesh		8	1,531	23.87%	2,091	99.50%
29	Plant-29	Madya Pradesh		6	1,527	26.13%	2,289	99.96%
30	Plant-30	Chhattisgarh		1	1,811	15.57%	1,364	85.79%
31	Plant-31	Andhra Pradesh	50 MWp to 150 MWp	6	2,003	16.74%	1,466	99.94%
32	Plant-32	Chhattisgarh		7	1,876	16.20%	1,420	99.60%
33	Plant-33	Kerala		7	1,599	15.81%	1,385	99.97%
34	Plant-34	Gujarat		3	2,148	19.20%	1,682	99.80%
35	Plant-35	Andhra Pradesh		5	2,063	21.38%	1,873	99.94%
36	Plant-36	Rajasthan		3	2,153	19.69%	1,725	99.73%
37	Plant-37	Gujarat		3	2,108	20.00%	1,752	99.67%
38	Plant-38	Rajasthan		1	2,170	19.83%	1,737	99.40%
39	Plant-39	Andhra Pradesh	150 MWp to 300 MWp	4	1,954	25.86%	2,266	99.99%
40	Plant-40	Rajasthan		2	1,930	25.94%	2,273	99.54%
41	Plant-41	Gujarat		4	1,984	19.05%	1,669	99.60%
42	Plant-42	Gujarat		3	2,108	19.17%	1,679	99.68%
43	Plant-43	Rajasthan		2	2,286	20.92%	1,832	99.79%
44	Plant-44	Madhya Pradesh		1	1,988	17.84%	1,562	99.46%
45	Plant-45	Rajasthan	Greater than 300 MWp	2	2,068	20.29%	1,777	99.91%
46	Plant-46	Rajasthan		3	2,068	19.58%	1,715	99.99%
47	Plant-47	Gujarat		2	2,199	20.70%	1,813	99.06%

Sl.No.	Plant	State/UT	Capacity	Age of Plant	Actual GHI	CUF	Specific Yield	Plant Availability
			MWp	Years	kWh/m^2	%	MWh/MWp	%
48	Plant-48	Tamil Nadu	Greater than 300 MWp	8	1,773	15.67%	1,372	99.68%
49	Plant-49	Rajasthan		2	1,890	18.62%	1,631	99.79%
50	Plant-50	Rajasthan		2	2,213	19.92%	1,745	99.81%
51	Plant-51	Rajasthan		2	2,036	19.43%	1,702	99.91%
52	Plant-52	Rajasthan		1	2,255	18.62%	1,631	99.32%
53	Plant-53	Rajasthan		2	2,268	20.23%	1,772	99.65%
54	Plant-54	Rajasthan		1	2,314	19.80%	1,735	99.61%

Key Findings:

1. National Performance Benchmarks

As per the dataset of CII Performance Excellence Awards covering multiple geographies, capacities, and irradiation regimes, the national solar performance stabilizes around the following benchmarks:

- National Average CUF: 18.5 %
- Best-in-Class CUF Range: 24% - 26% *(Observed in large-scale plants in Rajasthan, Madhya Pradesh, and Andhra Pradesh)*
- Underperforming / Low CUF Range: 14% – 16%
  (Typically seen in low irradiation regions or sub-optimally performing plants in states Delhi, Maharashtra, and older Tamil Nadu assets)
- National Average Specific Yield: 1,650 MWh/MWp
- National Average GHI: 1,900 kWh/m²
- National Average Plant Availability: 98.9%

Solar performance in India demonstrates **strong dependence on irradiation (GHI)**
CUF variation (~14% to ~26%) highlights **significant scope for performance optimization**
Availability across plants indicates a **mature O&M ecosystem**, with isolated exceptions

2. State-Level Performance Benchmarking

Solar performance shows clear regional dependence driven by irradiation levels, climate conditions, and plant design practices.

State-wise Benchmark Table

State	Average GHI (kWh/m²)	Average Plant Availability	Average CUF	Average Specific Yield (MWh/MWp)	Best-in-Class CUF
Rajasthan	2,100–2,300	99.7%	19–26%	1,700–2,270	26%
Gujarat	2,000–2,200	99.6%	19–21%	1,650–1,800	21%
Andhra Pradesh	1,850–2,050	99.9%	18–25%	1,600–2,260	26%
Karnataka	1,500–2,300	99.9%	15–21%	1,280–1,815	21%
Tamil Nadu	1,600–2,000	99.5%	15–18%	1,370–1,600	18%
Telangana	1,600–1,950	99.7%	14–24%	1,300–2,135	24%
Madhya Pradesh	1,500–2,000	99.9%	18–26%	1,560–2,289	26%
Maharashtra	1,500–2,000	99.9%	14–22%	1,250–1,980	23%
Kerala	1,600–2,000	99.9%	15–17%	1,380–1,490	17%
West Bengal	1,600	99.6%	15%	1,347	15%
New Delhi	1,300	99.9%	14%	1,200	14%

3. Technical Justifications for Performance Trends

Key Driver 1: Solar Irradiation (GHI) vs. Energy Yield

Solar plant performance is fundamentally driven by **Global Horizontal Irradiance (GHI)**.

- Rajasthan and Gujarat consistently achieve **CUF >19–26%** due to high irradiation (2,100–2,300 kWh/m²)
- In contrast, Delhi (1,300 kWh/m²) shows **low CUF (~14%)**, directly reflecting weaker solar resource

Key Driver 2: Scale and Technology Advantage (Utility-scale Case)

Large-scale plants (>150 MWp) demonstrate **superior performance benchmarks**:

- Large plants in Andhra Pradesh & Rajasthan achieve **CUF ~25–26%**
- Specific yield >2,200 MWh/MWp
- Use of Trackers

Key Driver 3: Regional Climate Effects (Humidity, Temperature, Soiling)

Certain states exhibit lower performance despite moderate irradiation:

Kerala & West Bengal

- High humidity and cloud cover
- Frequent diffuse radiation → lower energy conversion
- Result: CUF limited to 15–17%

Tamil Nadu

- High ambient temperature → module efficiency loss
- Aging plants → degradation impact

Summary

- **National CUF Benchmark:** ~18.5%
- **Top Performing States:** Rajasthan, Gujarat, Andhra Pradesh, Madhya Pradesh
- **Moderate Performers:** Karnataka, Tamil Nadu, Telangana

4. Specific Yield and Capacity Utilization Factor (CUF)

The performance data presented above table may be used as benchmark values based on the plant age and the annual solar irradiation (kWh/m²/year) received at the respective location.

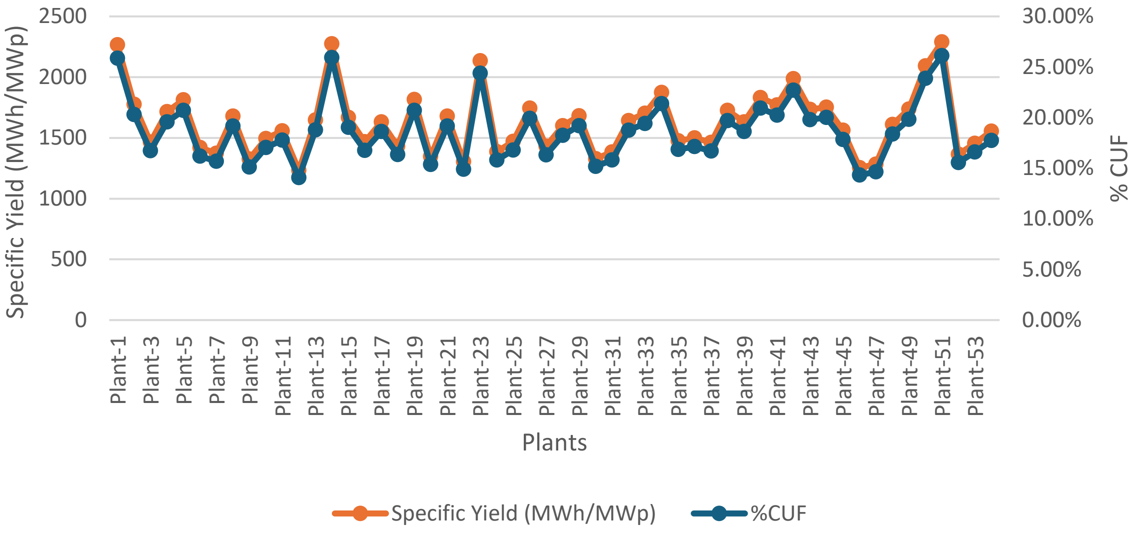

Figure 1: Variation of specific yield and capacity utilization factor

As per the data presented above, a variation of 46% in Energy Yield (MWh/MWp) and 46.2% in Capacity Utilization Factor (CUF) is observed between the best-performing and least-performing plants.

The performance of a solar power plant depends on several factors, including:

- Type of module technology used
- Type and efficiency of inverter deployed
- DC-to-AC ratio
- Mounting configuration, such as fixed tilt, seasonal tilt, single-axis tracker, or dual-axis tracker systems
- Operation and maintenance practices adopted

5. Wet and Dry Cleaning of Solar Modules

Based on the operational data submitted by participating plants in previous editions of the CII Performance Excellence Awards, benchmarking values for utility-scale solar plants adopting dry cleaning and wet cleaning methodologies have been analysed and presented below. The assessment highlights the operational and sustainability benefits associated with advanced module cleaning practices across large-scale solar installations.

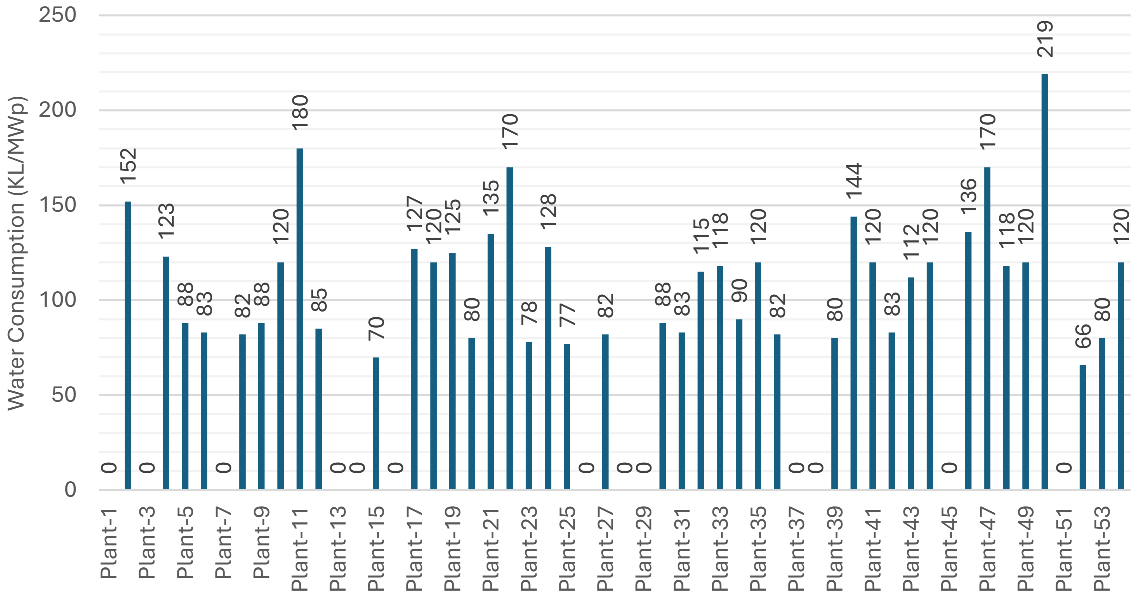

Figure 2:Specific Water consumption (kl/MWp) of utility scale solar power plants

The adoption of dry-cleaning systems offers significant advantages by substantially reducing water consumption, which is a critical consideration for solar projects located in water-stressed regions. In addition to water conservation, dry cleaning practices also contribute to energy savings by eliminating or minimizing the energy required for water pumping and associated cleaning operations

Table 4: Comparative Analysis of Wet and dry-cleaning method

Sr no.	Plant	Water Consumption (kl/MWp/Year) *	Pumping Energy Requirement (kWh/MWp/Annum)
1	Plant with wet cleaning technology	120 ~ 150**	33
2	Plant with Dry cleaning technology	0***	0

** Based on the water consumption shared by the GMS plants*

*** Based on plant cleaning cycle (2-3 times) every month, plants with less than 90 kl/MWp uses both wet and dry cleaning*

**** Plant has reported for wet cleaning they depend on the seasonal rainfall only*

Based on the water consumption data and operational practices reported by the participating plants, a back-calculation analysis has been carried out to estimate the potential energy savings achieved through the avoidance of water pump operation in utility-scale solar plants. The analysis demonstrates the combined environmental and operational benefits of sustainable cleaning practices in improving overall plant efficiency and resource optimization.

Table 5: Evaluation of Water Pump Energy requirement

Parameter	Value	Reference
Annual water consumption	150 kl/MWp/year	Benchmark observed in utility-scale solar plants as per plant presentations
Water density	1000 kg/m³	Standard density of water
Pumping head	50 m	Includes borewell depth, pipe losses, and elevation difference commonly observed in solar plants

Pump efficiency	70 %	Typical efficiency of centrifugal pumps used in industrial applications
Motor efficiency	90 %	Standard efficiency for industrial motors
Gravity constant	9.81 m/s²	Standard engineering constant

150 kl/Year = 150 m^3/Year

The hydraulic energy required for pumping water is:

$$E = \frac{\rho g H V}{\eta_p \eta_m}$$

Where,

- E= Energy required (Joules)
- V= Volume (m^3)
- ρ= Density of water (1,000 kg/m^3)
- g= Gravitational acceleration (9.81 m/s^2)
- H= Pumping head (50 m)
- η_p= Pump efficiency (0.70)
- η_m= Motor efficiency (0.90)

Substituting the values:

$$E = \frac{1000 \times 9.81 \times 50 \times 150}{0.70\ X\ 0.90}$$

$$E = \frac{7{,}35{,}75{,}000}{0.63}$$

$$E = 11{,}67{,}85{,}714.285 \text{ Joules}$$

$$1 \text{ kWh} = 3.6 \text{ X } 10^6 \text{ Joules}$$

therefor,

$$E = 32.44 \text{ kWh}$$

$$\sim 33 \text{ kWh/MWp/ Year}$$

In a traditional wet-cleaning system, a **1 MWp** solar power plant typically uses **150 kl** of water per year for module cleaning, with an additional **33 kWh** consumed per year for water pumping and associated operations.

Solar plants that use dry robotic cleaning systems can greatly reduce water use while removing the energy necessary for water handling and pumping. This not only increases operational sustainability but also helps to conserve resources, minimize O&M dependency, and improve the overall environmental performance of solar power plants.

Performance Improvement Study of Solar Plant

Performance improvement studies in solar power plants are essential for maximizing energy generation, improving operational efficiency, and ensuring long-term reliability of the plant. With continuous advancements in solar technologies, innovative operational strategies, and evolving industry best practices, there is significant potential to further enhance plant performance, optimize energy generation, improve operational efficiency, and maximize long-term asset reliability.

Objective of the study

- To identify, quantify and mitigate sources of performance loss in the solar plant, leading to enhanced Performance Ratio (PR), CUF and profitability.

A detailed performance improvement study helps identify generation losses, benchmark plant performance against design and industry standards, and recommend corrective measures for optimization. The study includes analysis of PR, specific yield, inverter performance, module health, system losses, cleaning practices, auxiliary consumption, and operational strategies.

Implementation of the identified improvement measures can help the plant achieve:

- Increased energy generation,
- Improvement in PR and CUF,
- Reduction in avoidable technical and operational losses,
- Optimized water and resource utilization,
- Improved equipment reliability and plant availability and
- Enhanced lifecycle performance and sustainability

CII-GBC can support plants in conducting comprehensive performance improvement studies through technical assessments, benchmarking, data analysis, best practice identification, and recommendation of actionable improvement measures based on industry expertise and operational excellence practices.

BEST PRACTICES FOR GROUND MOUNTED SOLAR PLANTS

Best Practice 1: Module Cleaning Practices in Ground Mounted Solar Plants

Module cleaning is an essential activity in ground mounted solar PV plants to maintain optimum irradiance absorption and energy generation performance. Factors such as dust deposition, climatic conditions, and environmental contaminants influence plant efficiency and cleaning frequency. Effective cleaning practices help sustain plant PR and long-term operational reliability.

Problem Statement:

Accumulation of dust, aerosols, and environmental contaminants on solar PV modules reduces irradiance absorption and impacts energy generation efficiency in ground mounted solar plants. Non-uniform soiling can also lead to hotspot formation, localized cell damage, degradation of module performance, and reduction in asset lifetime.

Solution Implemented:

Implementation of scheduled module cleaning through wet and dry-cleaning methods helps in effective removal of dust, aerosols, and other environmental contaminants from PV module surfaces. Wet cleaning is typically carried out twice per month, while dry cleaning is performed almost daily during the early morning and late evening hours to minimize soiling accumulation.

Figure 3:Manual Wet cleaning

Figure 4: Robotic dry cleaning

Figure 5: Air touch robots

Periodic cleaning minimizes soiling losses, reduces the risk of hotspot formation and localized cell damage, and supports consistent irradiance absorption across the module array. This contributes to improved plant PR, enhanced generation yield, optimized module health, and improved long-term operational reliability of the solar power plant.

One of the participating plant has installed **1,711 LEAPTING robotic** cleaning systems integrated with its tracker systems and a total of **970 Airtouch robotic** cleaning systems across its fixed-tilt solar installations.

Key Outcomes:

Table 6: Key Outcomes on performance parameters w.r.t dry and wet cleaning

Sl. No.	Plant	Cumulative Capacity of Plant MWp	Average CUF	Water Consumption (kl/Year)	Pumping Energy Requirement (kWh/Year)
1	Plant with dry cleaning technology	2,484	19.81 %	0	0*

2	Plant with wet cleaning technology	5,970	18.17 %	8,95,500	1,97,010

**Robotic dry cleaning is integrated with solar energy plants, can be seen in figure 3.*

Analysis of module cleaning practices based on operational data submitted by participating organizations during previous editions of the CII Performance Excellence Awards demonstrates the operational and sustainability benefits associated with dry-cleaning technologies in utility-scale solar PV plants. Solar installations with a cumulative installed capacity of 2,484 MWp implementing dry robotic cleaning systems reported negligible water consumption and auxiliary pumping energy requirements for module cleaning operations, while maintaining a higher average CUF of 19.81%.

In comparison, plants with a cumulative capacity of 5,970 MWp utilizing wet-cleaning systems reported annual water consumption of approximately 8,95,500 kl along with auxiliary pumping energy consumption of nearly 1,97,010 kWh per annum, with an average CUF of 18.17%. The assessment highlights the effectiveness of dry-cleaning technologies in reducing water intensity, minimizing parasitic energy consumption, and supporting enhanced operational efficiency and sustainable O&M practices in large-scale solar power plants.

Impact and Scalability:

Effective module cleaning improves irradiance transmittance, minimizes soiling losses, and supports sustained plant performance ratio (PR) and generation yield in utility-scale solar PV plants. Deployment of dry robotic cleaning systems significantly reduces water intensity and auxiliary energy consumption while enabling automated, scalable, and resource-efficient O&M practices across diverse plant capacities and climatic conditions.

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Renew	*Sugandha Mago*	*sugandha.mago@renew.com*

Best Practice 2: Module defect and degradation detection

Module defect and degradation detection refers to the process of identifying physical, electrical, and performance-related abnormalities in solar PV modules that may reduce energy generation efficiency and long-term reliability of the plant.

Problem Statement:

Environmental and electrical stresses can lead to defects such as hotspots, microcracks, delamination, and potential induced degradation (PID), resulting in reduced module performance and specific energy yield.

Solution Implemented:

Advanced diagnostic techniques including infrared thermography, electroluminescence (EL) imaging, I-V curve tracing, drone-based inspection, and SCADA analytics support early-stage fault detection, reduction in generation losses, and enhancement of plant performance ratio (PR) and asset reliability.

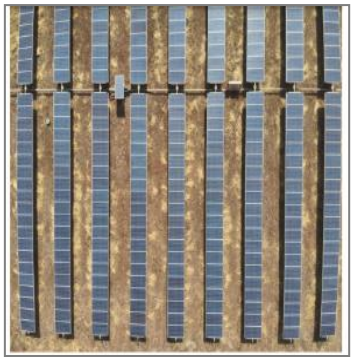


Figure 6: Real image of solar plant

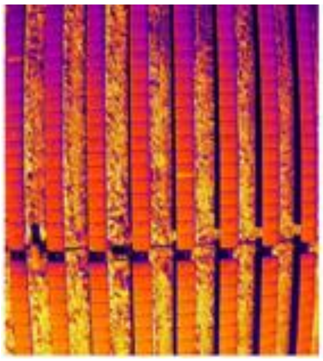


Figure 7: Thermal image of solar plant

Figure 8: Thermal inspection through thermal imaging camera

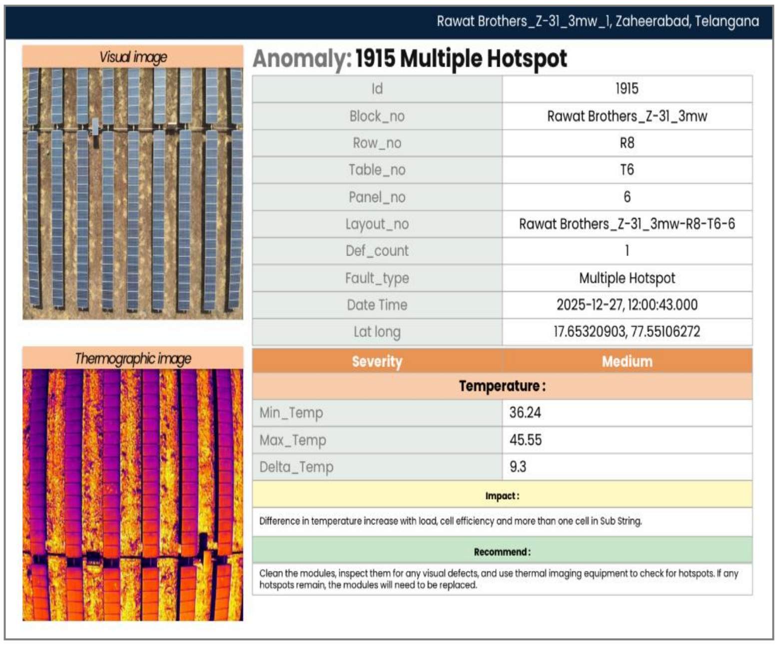
Key Outcomes:

The study enables early-stage identification of thermal anomalies, defective modules, and degradation patterns that may otherwise lead to generation losses, hotspot formation, accelerated module aging, and asset reliability issues. The study results provide detailed thermographic assessment of PV modules, including maximum and minimum module temperatures, along with precise string-wise and table-wise analysis of thermal anomalies and multiple hotspot locations across the solar plant.

One of the participating plants demonstrated the outcomes of the thermographic inspection and module degradation assessment study, the results of which are tabulated below:

Table 7: Thermography Test report

Description	Unit-1	Unit-2
Total Modules	37,268	37,352
Total Modules with Defects	60	23
Bypass Module	6	0
Short-Circuit	20	1
Low Voc	26	12
Hotspot at Junction Box	8	10



Rawat Brothers_Z-31_3mw_1, Zaheerabad, Telangana

Anomaly: 1915 Multiple Hotspot

Id	1915
Block_no	Rawat Brothers_Z-31_3mw
Row_no	R8
Table_no	T6
Panel_no	6
Layout_no	Rawat Brothers_Z-31_3mw-R8-T6-6
Def_count	1
Fault_type	Multiple Hotspot
Date Time	2025-12-27, 12:00:43.000
Lat long	17.65320903, 77.55106272
Severity	**Medium**
Temperature :	
Min_Temp	36.24
Max_Temp	45.55
Delta_Temp	9.3

Impact :

Difference in temperature increase with load, cell efficiency and more than one cell in Sub String.

Recommend :

Clean the modules, inspect them for any visual defects, and use thermal imaging equipment to check for hotspots. If any hotspots remain, the modules will need to be replaced.

Figure 9: Thermography report generated by thermal inspection

- This methodology significantly reduces inspection time compared to manual inspection practices.
- The high-accuracy assessment enables inspection of 100% of installed PV modules, eliminating dependency on limited sample-based inspection approaches.
- This help in improving the plant availability, optimised generation, and reduced downtime.

Impact and Scalability:

Deployment of thermographic inspection and module degradation assessment enables rapid fault identification, improved defect localization, and optimized condition-based maintenance in utility-scale solar PV plants.

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Best Practice 3: Improving Albedo to Enhance Bifaciality Factor

Albedo is the measure of ground surface reflectivity, which increases rear-side irradiance absorption in bifacial PV modules through increased diffused irradiance. Bifaciality factor represents the rear-side power generation capability of a bifacial module relative to its front-side output, indicating its effectiveness in utilizing reflected solar radiation for additional energy generation.

Problem Statement:

Sub-optimal ground reflectivity, inadequate module elevation, improper row spacing, and non-optimized site design can limit rear-side irradiance absorption in bifacial PV modules, resulting in inefficient utilization of bifacial generation capability. Ineffective management of albedo and array configuration reduces bifacial gain, limits energy yield enhancement potential, and impacts overall plant performance in utility-scale bifacial solar PV installations.

Solution Implemented:

Figure 10: Preparation of surface for improving the albedo[3]

Figure 11: Reflective sheet installation on surface[4]

As part of the plant's operational practices to enhance energy generation and maximize the benefits of the bifaciality factor, the plants have improved their surface albedo through the construction of white concrete surfaces and deployment of high-reflective ground materials beneath the module arrays. This enhanced rear-side diffuse irradiance and absorption contribute to improved bifacial gain and overall plant generation performance.

Key Outcomes:

Plant	Irradiance kWh/m^2/Annum	Plant Availability	Tracker Installed	Energy Gain Reported
Plant-1	1,988	99.46%	No	1.5-2%
Plant-2	2,108	99.67%	Yes	1.5-2%

3 Avaada Sunshine Energy Private Limited

4 Aditya Birla Renewable Limited

Both plants reported an energy gain of 1.5% - 2% because of albedo alone.

However, both plants have incorporated the practices on a pilot basis and are gaining benefits in terms of additional energy yield.

Impact and Scalability:

Enhancement of surface albedo using white concrete and high-reflective ground surfaces improves rear-side irradiance absorption in bifacial PV modules, resulting in an estimated generation gain of approximately 1.5–2%. The practice is scalable across utility-scale bifacial solar PV plants and supports improved bifacial gain and plant performance ratio (PR).

For more Information:

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Best Practice 4: Water Harvesting – Design Phase

Rainwater harvesting in solar plants involves collecting and storing rainwater for operational use and groundwater recharge. The harvested water is mainly utilized for solar module cleaning, gardening, and dust suppression activities. The system includes collection drains, filtration units, storage tanks, and recharge structures.

Problem Statement:

Large-scale solar power plants require substantial water resources for module cleaning and auxiliary activities, while many project locations face challenges related to water scarcity and declining groundwater levels. To address this concern, a comprehensive rainwater harvesting and groundwater recharge system has been integrated into the plant design for effective conservation and utilization of rainwater.

Solution Implemented:

Comprehensive rainwater harvesting and groundwater recharge system has been incorporated into the project design phase to effectively capture and utilize rainwater generated within the plant premises. Rainwater runoff from solar module areas and internal roads is collected through a well-planned drainage network and directed toward strategically located recharge wells and percolation pits. The collected water gradually percolates into the ground, helping recharge underground aquifers and improve groundwater availability. This initiative supports sustainable water management, reduces dependence on external water sources, and enhances the overall environmental sustainability of the solar power plant. The project is implemented by Avaada Sunshine Energy Private Limited.

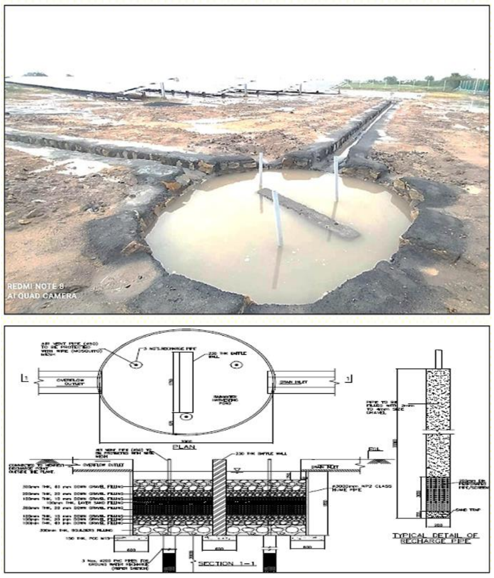

Figure 12: Rainwater Harvesting in Solar Plant[1]

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1 Avaada Sunshine Energy Private Limited

Key Outcomes:

Land Area (Acres)	Annual Rainfall (mm)	Water harvesting capacity (Lakh kl/Annum)	Project Cost (₹ lakhs)	Water uses/Application
971	900-950	7-11	100	Ground Water Recharge

Groundwater Recharge:
Recharge wells and percolation pits facilitate natural infiltration of rainwater into the ground, helping improve groundwater levels and ensuring long-term water availability.

Reduction in O&M Cost:
The initiative minimizes expenditure on water procurement through tankers and borewells, resulting in lower operational and maintenance costs over the project lifecycle.

Environmental and Community Benefits:
The practice improves the local water balance, supports sustainable resource management, and creates a positive environmental impact for nearby ecosystems and surrounding communities.

Effective Stormwater Management:
A planned drainage and recharge network helps prevent waterlogging, controls surface runoff, and minimizes soil erosion, thereby protecting plant infrastructure.

Figure 13: Outcomes of water harvesting

Impact and Scalability:

The rainwater harvesting and groundwater recharge system has enhanced sustainable water management by reducing dependence on external water sources and improving groundwater replenishment within the plant premises. The initiative supports long-term water availability for operational activities, minimizes stormwater runoff and soil erosion, and contributes towards reduction in O&M costs associated with water procurement.

The practice is highly scalable and can be replicated across utility-scale solar power plants with varying site conditions and rainfall patterns. The modular design of drainage networks, recharge wells, and percolation pits enables easy adaptation based on plant capacity, land availability, and local hydrogeological conditions, supporting wider adoption of sustainable water conservation practices in the renewable energy sector.

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Best Practice 5: Installation of Static VAR Generators

Reactive power management in grid-connected solar power plants is essential for maintaining **voltage stability**, enhancing **power quality**, and ensuring **reliable grid operation**. As renewable energy penetration increases, solar plants must dynamically control reactive power using SVGs (Static VAR Generators).

Problem Statement:

Integration of utility-scale solar power plants into the electrical grid is increasing, and maintaining voltage stability and power quality has become a major operational challenge. Solar generation is inherently variable because solar radiation is intermittent in nature, leading to rapid voltage variations and unstable reactive power demand at the grid interconnection point. Conventional reactive power compensation systems such as fixed capacitor banks often fail to provide fast and dynamic response under continuously changing operating conditions.

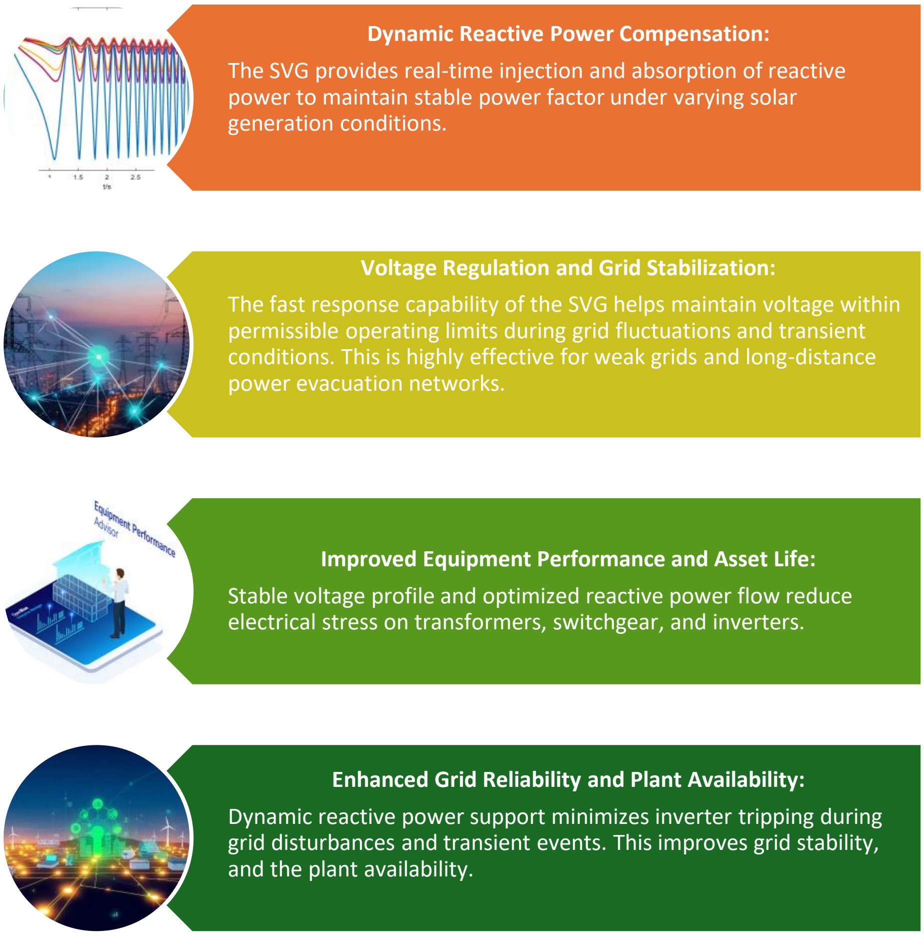
Solution Implemented:

Utility-scale plants are increasingly installing Static VAR Generators (SVGs), which have become essential for providing fast and continuous reactive power compensation, improving voltage regulation, enhancing grid stability, and ensuring reliable operation of the solar power plants in compliance with modern grid requirements.

Figure 14: Static VAR generators in solar plant

Base Scenario	Improved Scenario	Cost Savings
Elevated HT billing due to poor reactive power management, higher import lead reactive energy, and maximum demand penalties imposed by DISCOM	HT bill reduction achieved through advanced reactive power management via hardware and software upgradation	₹ 250 Lakhs/Annum

Key Outcomes:



Dynamic Reactive Power Compensation:

The SVG provides real-time injection and absorption of reactive power to maintain stable power factor under varying solar generation conditions.

Voltage Regulation and Grid Stabilization:

The fast response capability of the SVG helps maintain voltage within permissible operating limits during grid fluctuations and transient conditions. This is highly effective for weak grids and long-distance power evacuation networks.

Improved Equipment Performance and Asset Life:

Stable voltage profile and optimized reactive power flow reduce electrical stress on transformers, switchgear, and inverters.

Enhanced Grid Reliability and Plant Availability:

Dynamic reactive power support minimizes inverter tripping during grid disturbances and transient events. This improves grid stability, and the plant availability.

Figure 15: Key outcomes of installing static VAR generators

Impact and Scalability:

SVG-based reactive power compensation improved power factor, voltage stability, grid compliance, and overall power quality, resulting in reduction of HT bill penalties and improved plant reliability. The initiative is highly scalable and can be integrated across utility-scale solar plants through modular SVG systems and inverter–SCADA based reactive power control architecture.

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Best Practice 6: Implementation of Wireless String Monitoring System

A Wireless String Monitoring System is an advanced digital monitoring solution that enables real-time tracking of individual solar PV string performance through wireless communication. The technology continuously monitors key electrical parameters such as current, voltage, and power output to identify underperforming strings, faults, and generation losses, while reducing cabling complexity and improving operational visibility.

Problem Statement:

Solar plants generally rely on manual string current measurements using clamp meters, which is time-consuming and lacks continuous performance visibility. This makes it difficult to promptly identify underperforming strings and faults, leading to delayed corrective actions and reduced performance optimization. In most cases, a limited number of SCBs operate under low-performance conditions and are typically identified only after 1–2 years of plant operation, resulting in prolonged energy generation losses.

Solution Implemented:

As the integration of utility-scale solar power plants into the electrical grid increases, maintaining voltage stability and power quality has become a major operational challenge. The system utilizes wireless current sensing devices and a centralized web-based monitoring platform to enable continuous performance tracking, rapid fault identification, reduced dependency on manual inspections, and improved plant operational efficiency through optimized O&M practices

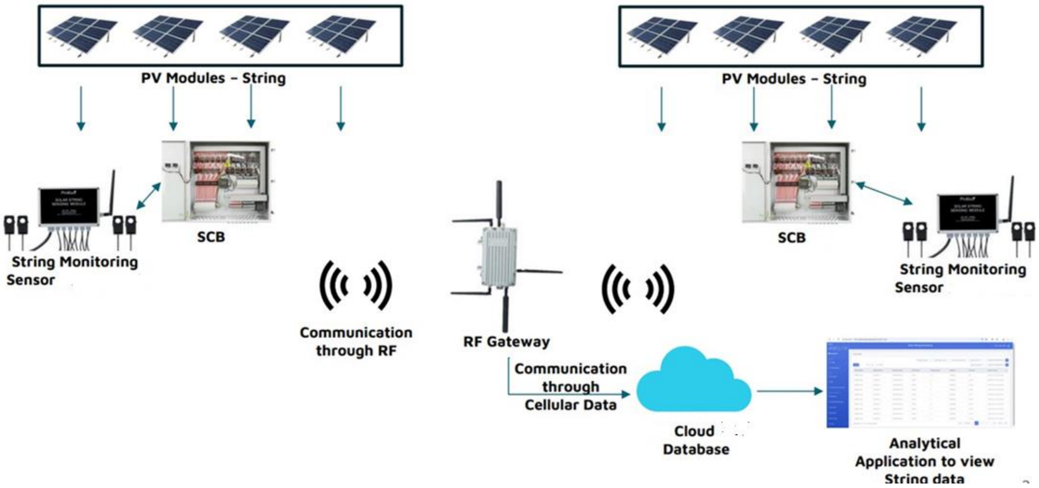

Figure 16: System Architecture

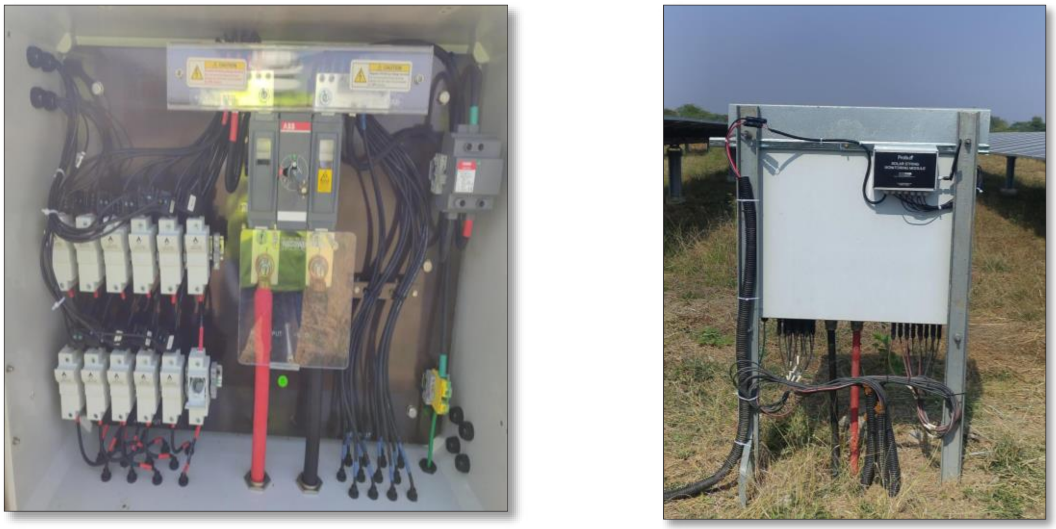

Figure 17: String Combiner Boxes

Key Outcomes:

Plant Down Time	Generation Improvement	Life of component	Monitoring System cost/String
Decreases	1-2%	Increases	₹ 1,200

- The solution is particularly beneficial in areas prone to high soiling & shadow loss.
- The solution supports sustainable, data-driven approach to operations by reducing manual inspections, lowering O&M manpower, and improving energy yield.
- Its scalable wireless architecture and compatibility with AI/ML analytics ensure long-term operational efficiency and future readiness.

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Best Practice 7: Digitalization of monitoring System

Digitalization of the monitoring system through deployment of an advanced integrated digital platform enables real-time performance monitoring, centralized data acquisition, and remote asset visibility across plant operations. The initiative enhances operational efficiency through continuous performance analytics, automated fault detection, and predictive decision-making based on data-driven insights.

Problem Statement:

Limited real-time visibility, delayed fault detection, and manual reporting practices in solar plants result in reduced Performance Ratio (PR), increased operational downtime, and delayed corrective actions, thereby impacting overall plant performance and energy generation efficiency.

Solution Implemented:

An advanced *Data-Driven Performance Monitoring System* has been deployed to address critical operational challenges associated with solar plant performance management. The system integrates data from multiple plant-level sources into a centralized digital platform, enabling real-time performance monitoring, automated analytics, and early identification of operational deviations and equipment abnormalities.

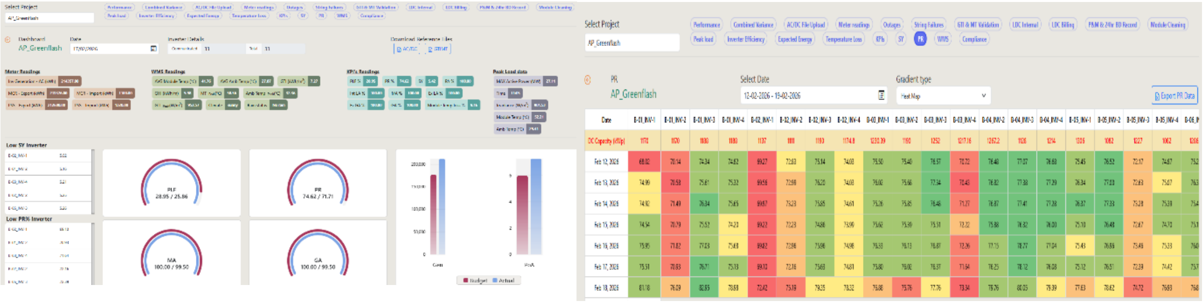

Figure 18: Dashboard of digital monitoring system

The implementation enhances operational visibility, improves Performance Ratio (PR), reduces plant downtime, minimizes dependency on manual reporting processes, and enables data-driven decision-making for optimized asset utilization, improved system reliability, and enhanced energy generation performance.

Key Outcomes:

LANT RUNNING STATISTICS

Jilesh

Current Generation	11.9 MW
Current Export	22.2 MW
Today's Export	257 MWh
Today's Import	600.000 MWh
Current PR	145%
Current PLF	65.7
POA Irradiance	790 W/m²
POA Acc	5.25 Wh/m2
GH IRR	685 W/m²
GHI Acc	4.75 Wh/m2
Ambient Temperature	32.1 °C
Average Ambient Tempe...	29.5 °C
Max Ambient Temperature	33.0 °C
Module Temperature	53.2 °C
Average Module Temper...	50.6 °C
Max Module Temperature	69.0 °C
Wind Speed	6.43 m/s
Today's day Auxiliary (kW)	53000
Today's Night Auxiliary E...	
Today's PLF	31.6%
Online	49
Ready	0
Offline	0
No Conn	29
Total inverters	49

AY STATISTICS

Jilesh

Figure 19: Performance output from digital monitoring system

Table 8: Key benefits on performance parameters by integration of digital monitoring system

Benefits	Before the project	After the project
Plant Availability (%)	99.30 %	99.50 %
Down time (%)	0.70 %	0.50 %
Generation Specific Yield (MWh/MWp/Annum)	1,700	1,708–1,710
Operation and maintenance Cost (Lakhs ₹/MWp/Annum)	3.43	3.40

Impact and Scalability:

The solution is highly scalable and can be replicated across utility-scale and multi-location renewable energy assets through seamless integration with existing plant monitoring and SCADA systems, supporting long-term digitalization and intelligent asset management.

For more Information:

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Best Practice 8: Data-Driven cleaning schedule based on local soiling conditions in the lant

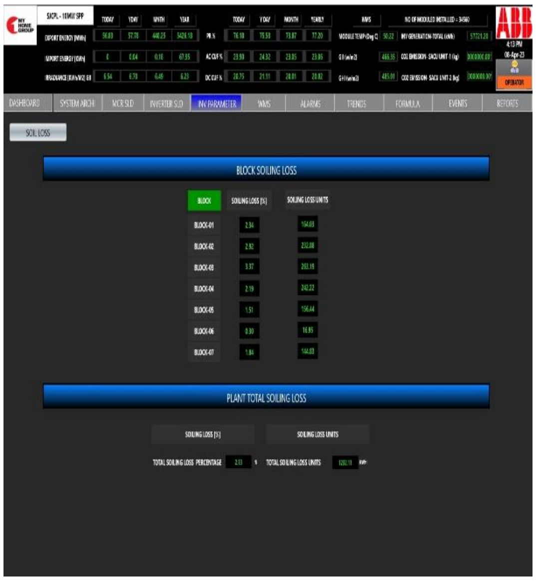
Data-driven cleaning technology in solar PV plants utilizes real-time soiling monitoring, weather analytics, and performance data to optimize module cleaning schedules based on actual site conditions. The system analyzes dust accumulation, rainfall patterns, and generation losses to identify the optimal cleaning interval.

Problem Statement:

Conventional fixed cleaning schedules in solar PV plants often result in either excessive water consumption and higher O&M costs or increased energy losses due to delayed cleaning. Since soiling levels vary with local weather and site conditions, there is a need for a data-driven cleaning approach to optimize cleaning frequency, reduce resource consumption, and improve plant performance.

Solution Implemented:

The plant comprises a **11.4 MWp** solar PV installation located adjacent to a cement manufacturing facility, where significant cement dust deposition on PV modules adversely affects solar irradiance absorption and overall energy generation performance. Earlier, module cleaning activities were carried out without assessment of actual soiling conditions, resulting in higher soiling losses, reduced plant Performance Ratio (PR), and avoidable energy generation losses.



BLOCK	SOILING LOSS [%]	SOILING LOSS UNITS
BLOCK-01	2.34	164.03
BLOCK-02	2.92	232.88
BLOCK-03	3.37	263.19
BLOCK-04	2.19	242.22
BLOCK-05	1.51	156.44
BLOCK-06	0.30	16.95
BLOCK-07	1.84	144.83

Figure 20: Dashboard for onsite soiling analysis

An intelligent soiling assessment logic was integrated into the existing ABB PLC and SCADA system using a reference solar table cleaned daily for baseline performance comparison. The system continuously identifies soiling-affected strings, inverters, and blocks through real-time performance deviation analysis, enabling targeted cleaning of dust-prone areas near the cement plant. This approach optimizes cleaning operations, reduces unnecessary water and manpower usage, and minimizes energy generation losses due to module soiling.

Key Outcomes:

Description	Unit	2021-22	2022-23	2023-24	2024-25	2025-26
Energy Generated	MWh	15,737	16,754	17,692	17,010	16,465
Loss Due to Soiling	MWh	518	366	358	324	294
% Soiling Loss	%	3.36	2.21	2.03	1.91	1.78

Description	Before	After
Frequency of Cleaning	10 random cycles per month	8 targeted cycles per month
Water Consumption	3 to 4 litters per module	2 to 2.5 litres per module

- **Improved generation**: Plant has reduced soiling losses by 50% from 3.36% to 1.78%, form 2021-22 level, resulting in additional generation of 225 MWh of energy per year.
- **Reduced frequency of cleaning**: No. of cleaning cycles reduced 10 to 8 every month and this saves 24 full cleaning cycles every year
- **Saved Water**: Water usage reduced from 3.5 to 2.5 litres/ panel
- **Reduced O&M Cost**: Reduced cleaning Manpower

Impact and Scalability:

The solution is highly scalable and can be replicated across utility-scale solar PV plants, particularly in high-dust environments such as cement, mining, and industrial zones, through integration with existing PLC, SCADA, and plant monitoring systems.

For more Information:

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WIND

Brief Scenario of Wind Plants in India

Wind power plants form a critical pillar of India's renewable energy portfolio, contributing significantly to clean power generation and grid stability. As of March 2026, India's installed wind capacity has crossed approximately **56 GW** [11], making it one of the largest onshore wind markets globally. Wind projects are predominantly concentrated in high-resource states such as Tamil Nadu, Gujarat, Karnataka, Maharashtra, and Rajasthan, where favourable wind regimes and established infrastructure support large-scale deployment.

The sector's growth has been driven by sustained policy and regulatory support from the Ministry of New and Renewable Energy and market frameworks shaped by the Central Electricity Regulatory Commission. Interstate transmission connectivity and Green Energy Corridor initiatives have facilitated the evacuation of wind power from resource-rich regions to demand centres.

Technological advancements in wind turbine generators—such as increased hub heights, larger rotor diameters, and improved control systems—have led to higher capacity utilization factors (CUFs) and better performance across varying wind regimes. Modern wind plants are increasingly supported by digital monitoring systems, predictive maintenance practices, and centralized control centres, enabling improved reliability and reduced operational downtime.

However, the sector continues to face challenges related to land acquisition, transmission constraints in high-potential zones, increased system complexity, which introduces additional maintenance requirements and the need for specialized expertise to manage advanced control systems, sensors, and auxiliary equipment. The sector also faces variability in state-level policies. Repowering of older wind turbines and the development of offshore wind projects are emerging as key opportunities to unlock additional capacity and enhance generation efficiency.

Overall, wind power plants in India are poised for steady growth, supported by enabling policies, technological innovation, and a strong project pipeline. The sector will continue to play a crucial role in achieving India's target of **500 GW of non-fossil fuel capacity by 2030** [13], contributing to a diversified, resilient, and sustainable energy ecosystem.

Table 9: Performance Parameters of Wind Plants [14]

Sl. No.	Plant Name	State	Capacity (MW)	Age of Plant Years	Hub Height (m)	Wind Power Density (W/m2)	Plant Availability (%)	CUF (%)
1	Plant-1	Tamil Nadu	Up to 50 MW	14	80	200	99%	31%
2	Plant-2	Tamil Nadu		14	106	300	98%	35%
3	Plant-3	Tamil Nadu		14	78.2	200	98%	24%
4	Plant-4	Karnataka		10	85	291	99%	28%
5	Plant-5	Maharashtra		3	140	258	97%	36%
6	Plant-6	Tamil Nadu		17	78.5	200	98%	24%
7	Plant-7	Tamil Nadu		18	80	200	98%	25%
8	Plant-8	Gujarat		5	120	183	99%	35%
9	Plant-9	Maharashtra		17	76	139	99%	21%
10	Plant-10	Gujarat		5	140	269	97%	32%
11	Plant-11	Maharashtra		13	85	262	99%	23%
12	Plant-12	Gujarat		5	120	269	98%	27%
13	Plant-13	Karnataka		11	88	256	96%	30%
14	Plant-14	Gujarat		2	118	269	99%	35%
15	Plant-15	Karnataka		6	140	265	98%	27%
16	Plant-16	Rajasthan		25	85	223	97%	24%
17	Plant-17	Gujarat		4	140	269	99%	31%
18	Plant-18	Tamil Nadu		15	78.5	200	98%	24%
19	Plant-19	Karnataka		12	88	200	97%	25%
20	Plant-20	Madhya Pradesh	50 MW to 150 MW	9	106	350	99%	30%
21	Plant-21	Maharashtra		3	130	204	99%	29%
22	Plant-22	Andhra Pradesh		8	90	242	96%	24%
23	Plant-23	Tamil Nadu		2	140	221	99%	31%
24	Plant-24	Andhra Pradesh		1	140	225	98%	33%
25	Plant-25	Maharashtra		13	80	220	98%	23%

Sr No	Plant Name	State	Capacity (MW)	Age of Plant Years	Hub Height (m)	Wind Power Density (W/m2)	Plant Availability (%)	CUF (%)
26	Plant-26	Andhra Pradesh		7	120	244	98%	22%
27	Plant-27	Andhra Pradesh		9	106	346	99%	32%
28	Plant-28	Rajasthan		9	90	223	99%	15%
29	Plant-29	Madhya Pradesh		8	104	207	98%	23%
30	Plant-30	Karnataka		6	106	223	99%	29%
31	Plant-31	Rajasthan		8	104	223	98%	21%
32	Plant-32	Tamil Nadu		13	85	200	98%	23%
33	Plant-33	Gujarat	More than 150 MW	2	140	269	99%	37%
34	Plant-34	Karnataka		4	127	278	98%	35%
35	Plant-35	Andhra Pradesh		12	90.3	237	98%	23%
36	Plant-36	Madhya Pradesh		2	130	350	96%	30%
37	Plant-37	Gujarat		1	140	300	99%	34%
38	Plant-38	Andhra Pradesh		7	90	263	97%	25%
39	Plant-39	Gujarat		25	120	157	99%	35%

Hub Height Range	Min CUF	Max CUF	Avg CUF
< 90 m	20.6%	30.8%	25.1%
90 m – 109 m	15.4%	34.8%	25.4%
110 m – 129 m	25.1%	35.4%	32.0%
≥ 130 m	29.0%	36.7%	32.7%

- Average CUF increases with hub height from 25.1% (90 m hub height) to 32.7% (30 m hub height)

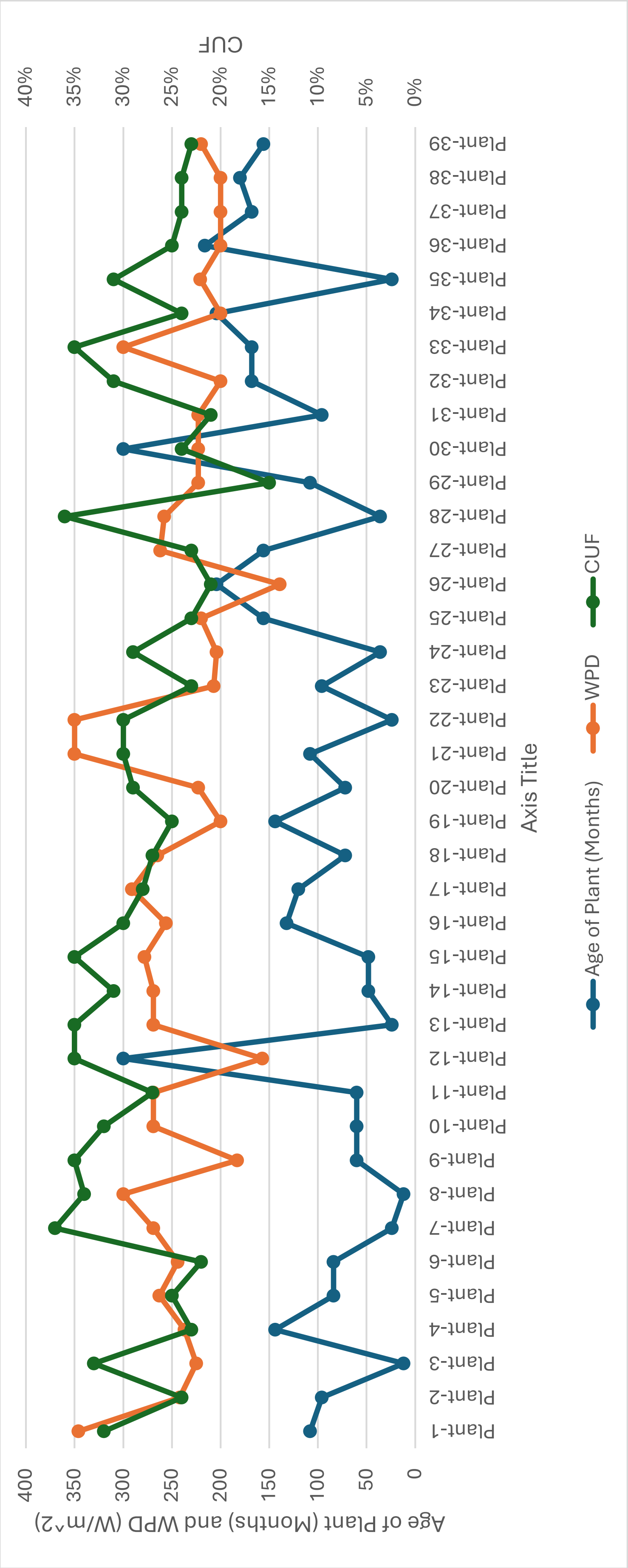

Figure 21: Wind Plants performance curve w.r.t the age

Observations:

1. National Performance Benchmarks

Across the entire dataset of CII Performance Excellence Awards, representing a diverse mix of geography, technology eras, and resource regimes, the national wind performance indicators settle into the following benchmarks:

- **National Average Capacity Utilization Factor (CUF):** 27.97 % [14]
- **Best-in-Class CUF Range:** 34 % - 37 % (*Led by modern installations in Gujarat and Karnataka)*
- **Underperforming/Low CUF Range:** 15 % - 23 % *(Typically seen in legacy assets or regions with lower wind regimes like Rajasthan)*
- **National Average Plant Availability:** 98.18 % *(Reflecting highly mature and standardized Operations & Maintenance (O&M) practices across the country)*

2. State-Level Performance Benchmarking

Wind performance in India is highly regional due to localized wind corridors, monsoon patterns, and varying state-level grid infrastructure.

State	Total Capacity (MW)	Average Age (Years)	Average Hub Height (m)	Average Wind Power Density (W/m2)	Average Plant Availability	Average CUF	Best-in-Class CUF
Gujarat	911	6.1	129.8	248.1	99%	33%	37%
Karnataka	489	8.2	105.7	252.2	98%	29%	35%
Madhya Pradesh	479	6.3	113.3	302.4	98%	28%	30%
Tamil Nadu	290	13.4	90.8	217.6	98%	27%	35%
Andhra Pradesh	844	7.3	106.1	259.5	98%	27%	33%
Maharashtra	312	9.8	102.2	216.6	99%	26%	36%
Rajasthan	267	14	93	223	98%	20%	24%

3. Technical Justifications for Performance Trends

Key Driver 1: Wind Power Density (WPD) vs. Hub Height Optimization

While Wind Power Density is a critical site-specific metric, the ability to exploit it depends heavily on Hub Height.

For example, **Plant-33** in Gujarat and **Plant-36** in Madhya Pradesh have comparable metrics, but Plant-33 reaches a 140 m hub height and achieves a remarkable 37 % CUF, whereas Plant-36 achieves 30 % with a 130 m hub height.

Key Driver 2: Regional Anomalies and Grid Curtailment (The Rajasthan & Maharashtra Case)

Rajasthan shows the lowest benchmark performance across India with an average CUF of 20 %. This is justified by two primary factors:

1. **Extreme Seasonality:** Wind resources in Rajasthan are highly concentrated during the pre-monsoon and monsoon months, with prolonged low-wind intervals during winter.
2. **Grid Integration Challenges:** Regions with concentrated solar and wind capacities often suffer from grid curtailment during peak generation hours.

Key Driver 3: Legacy Site Advantages (Tamil Nadu)

Tamil Nadu features some of the oldest wind plants in the dataset, with an average plant age of 13.4 years and an average hub height of 90.8 m. Despite these characteristics, the state records a strong benchmark CUF of 27.13%. This observation highlights the ability of well-established wind projects to sustain high levels of performance over time, reflecting the combined influence of favourable wind resources, asset reliability, and effective operational and maintenance practices.

Best Practice 1: Improvement in IGBT Thermal Management and Dust Ingress Control

In wind turbine systems, Insulated Gate Bipolar Transistors (IGBTs) play a critical role in efficient power conversion and control operations. The performance and reliability of IGBTs are highly dependent on effective thermal management and protection against environmental contaminants such as dust and moisture ingress. Restricted airflow, inadequate cooling, and contamination can lead to overheating, accelerated component degradation, and eventual IGBT failure, adversely impacting turbine availability and operational reliability.

Problem Statement:

Frequent **IGBT failures** were due to moisture and dust ingress, poor cooling air circulation, and limited spare availability in the supply chain, combined with commercial challenges. This led to higher maintenance costs and reduced turbine uptime.

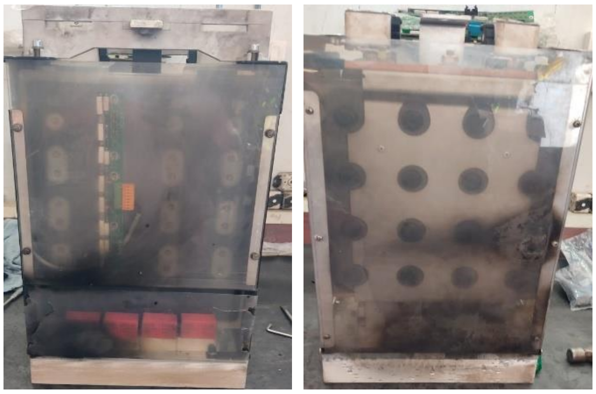

Figure 22:IGBT failures in Wind Turbine Generator

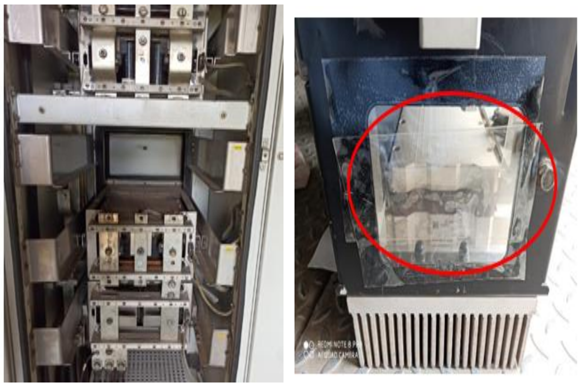

Figure 23:Modification done in IGBT Stacks

Solution Implemented:

Brush strips were inserted between the IGBTs to improve airflow and regulate temperature. These strips were carefully designed to withstand extreme heat and resist fire hazards, ensuring durability under demanding conditions. At the same time, holes in the cooling air filter ducts were sealed to prevent leakage, and rubber beadings on panel doors were replaced to block dust and moisture from entering the system. Together, these measures created a more controlled environment for the IGBTs, reducing overheating and contamination while improving overall reliability.

Key Outcomes:

The interventions reduced IGBT failures from 59 in FY-2019-20 to just 5 in FY-2023-24, resulting in significant maintenance cost savings, minimised downtime, and improved turbine availability. With fewer breakdowns, energy generation became more consistent and reliable.

Table 10:Year Wise improvement in IGBT failure

Plant	FY 2019-20	FY 2020-21	FY 2021-22	FY 2022-23	FY 2023-24	Reduction in fault occurrences/₹ Saving with reference to 2019-20
Plant 1 - (Nos)	59	24	9	6	5	54
Plant 2 - (Nos)	84	57	49	32	19	65
Total Occurrences	143	81	58	38	24	119
Expense for IGBT to ISP/OEM (₹ Lakhs)	298.87	169.29	121.22	79.42	50.16	248.71
Total Cost for Break Down (₹ Lakhs)	319.99	181.25	129.78	85.03	53.70	266.29

Impact and Scalability:

The solutions apply **to both small and large wind farms**. They work well for **onshore projects**, where IGBT failures are often associated with elevated operating temperatures; however, the occurrence and frequency of such failures may also be influenced by equipment design limitations and the suitability of the original converter configuration for local climatic conditions.

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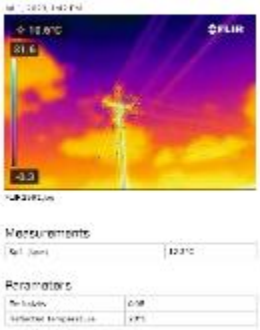
Best Practice 2: Condition Monitoring of Power Evacuation Infrastructure through Thermography

Periodic inspection of power line evacuation from wind plants, including thermography for Extra High Voltage (EHV) lines, is critical to ensure reliability, and prevent failures. Thermography helps detect hotspots and insulation issues early, reducing the risk of outages and equipment damage.

Problem Statement:

Frequent tripping of high-voltage power evacuation lines due to insulator failures and associated reliability issues can create significant operational challenges and increase the risk of generation loss. Such recurring incidents highlight the need for proactive condition monitoring, quality assessment, and timely corrective measures to ensure reliable power evacuation and stable plant operations.



Solution Implemented:

Proactive thermographic inspection of the power evacuation line was carried out to identify weak and defective insulators based on thermal abnormalities. Identified insulators were replaced through hotline maintenance on live circuits and offline replacement during load transfer conditions to minimize generation loss. Additionally, preventive thermography was conducted prior to scheduled line maintenance for early detection and replacement of vulnerable insulators, thereby improving evacuation line reliability and operational stability.

Activity	Description	Quantity / Details
Insulator Thermography	Thermography carried out to identify weak or suspected insulators	Complete inspection conducted
Hotline Insulator Replacement	Replacement of insulators on live circuits using hotline method	243 insulators replaced
Offline Insulator Replacement	Replacement of insulators after shifting load to another circuit	405 insulators replaced
Total Insulators Replaced	Total replacement carried out based on thermography findings	648 insulators replaced
Pre-Maintenance Thermography	Thermography conducted before line maintenance	3 weak insulators identified and replaced

Parameter	FY 24–25	FY 25–26	Improvement Achieved
Insulator Failure Events	5	0	Complete elimination of failure events
Generation Loss	Higher generation loss observed	8.9 MU/annum avoided	Reduction in generation loss
Financial Impact	Higher revenue loss observed	₹247.3 Lakhs/annum avoided	Improvement in revenue realization

- Frequent tripping of the 220 kV line was reduced after replacing weak insulators.
- Thermography identified weak insulators in advance, allowing timely replacement during maintenance shutdown.

Impact and Scalability:

Periodic thermographic inspection is scalable across wind plants of any size. It is particularly effective for large evacuation lines where reliability is critical and can be applied to both onshore and offshore projects.

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Best Practice 3: Improvement in Cable Grip Stability and Surge Protection Measures

The modification in the clamp arrangement improves cable holding strength and prevents cable slippage caused by vibration, wind load, or mechanical stress during operation. At the same time, installation of additional lightning arrestors enhances protection against lightning surges and transient over voltages, reducing the risk of equipment damage, insulation failure, and system outages.

Problem Statement:

Power cables which are inside the wind tower were found slipping from their clamps. This created risks of cable overload, insulation damage, short circuits, and fire hazards. The issue required immediate resolution to safeguard turbine reliability and safety. During WTG preventive maintenance inspections, power cables were observed sliding downward from the holding clamps inside the tower. This posed risks of uneven stress, insulation damage, and potential fire hazards.

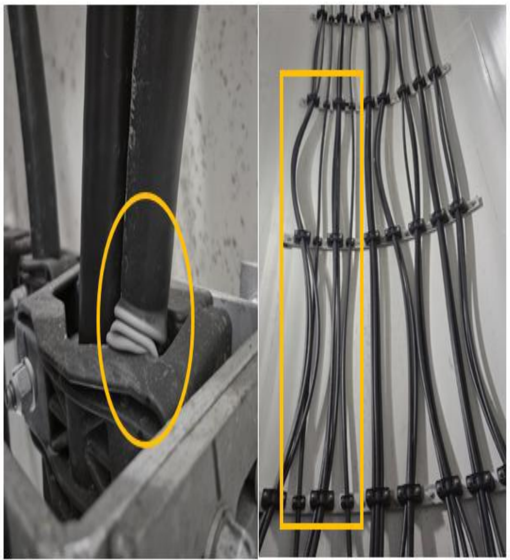

Figure 24: Cable inside the tower before initiative

Figure 25: Cables arrangement after the retrofit

Solution Implemented:

The intermediate part of the clamp was removed to improve grip and prevent cable sliding. Additional lightning arrestors were installed to enhance system protection. Special arrangements, such as internal sky-lift systems, were used to carry out the corrective work safely and efficiently.

Key Outcomes:

Parameter	Improvement Achieved
Generation Loss Reduction	2.5 MU generation loss avoided annually
Financial Savings	₹ 64 lakh annual savings
Breakdown time Reduction	Approx 4000 breakdown hours

Impact and Scalability:

This solution is scalable across wind plants of any size, especially where vertical cable runs inside towers are common. By standardising clamp modifications and periodic inspections, operators can prevent similar failures in both onshore and offshore projects.

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Best Practice 4: Operational Efficiency Improvement through Wind Turbine Blade Cleaning

WTG Blade Cleaning is a preventive maintenance activity carried out to remove dust, dirt, and surface contaminants from wind turbine blades that affect aerodynamic performance and reduce energy generation efficiency. Regular cleaning improves blade efficiency, enhances power generation, and supports reliable turbine operation.

Problem Statement:

During regular performance monitoring and analysis, significant underperformance is observed in certain WTGs. Detailed investigation identifies heavy dust deposition on turbine blades, resulting in aerodynamic inefficiencies. The dust deposition altered the aerodynamic profile of the blades, resulting in reduced lift efficiency, increased drag, and lower energy conversion performance. Continuous accumulation of contaminants also increased mechanical loading on the turbine system, adversely affecting overall generation performance and operational reliability.

Solution Implemented:

A systematic blade cleaning activity was carried out for underperforming WTGs using man-basket arrangements for safe access to turbine blades.

Figure 26: Team during WT blade cleaning

Figure 27: After cleaning the blade

Cleaning was performed using water and biodegradable non-abrasive cleaning agents to effectively remove dust and surface contaminants without damaging the blade surface.

Low-pressure washing techniques were adopted to protect blade coating integrity and prevent surface erosion. The cleaning process was executed methodically from the leading edge to the trailing edge to ensure complete removal of deposits. Post-cleaning inspection was conducted to verify blade cleanliness, surface smoothness, and absence of residual contaminants for restoring optimal aerodynamic performance.

Key Outcomes:

Regular cleaning enhances energy generation, improves turbine reliability and operational efficiency, and helps maintain optimal blade condition. The activity also supports extension of blade operational life by reducing surface degradation and leading-edge erosion.

Parameter	Improvement Achieved
Energy Generation	Increased by approximately 10%–12% (Nov to May)
Turbine Performance	Improved reliability and operational efficiency
Blade Condition	Extended blade operational life and reduced leading-edge erosion
Total Investment	₹ 12 Lakhs
Payback	1 Month

Impact and Scalability:

The practice is highly scalable and can be implemented across wind power plants, particularly in high-dust environments, to improve turbine performance and blade life.

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Best Practice 5: Condition-Based Monitoring for WTG Reliability Enhancement

Wind turbine condition-based monitoring is a predictive maintenance system that continuously monitors turbine health using sensors and real-time data analytics. The system enables early fault detection, reduces downtime, and improves turbine reliability and operational efficiency.

Problem Statement:

Conventional maintenance practices primarily rely on periodic inspections and breakdown-based maintenance, making it difficult to detect early-stage equipment degradation and potential failures. As a result, unexpected component failures lead to prolonged turbine downtime, delayed maintenance response, higher operational costs, and reduced energy generation.

Solution Implemented:

An advanced Condition-Based Monitoring (CBM) system was implemented across wind turbine generators to enable predictive maintenance through continuous monitoring of critical turbine components. The system utilizes real-time sensor data and advanced analytics to assess equipment health, support early fault detection, optimize maintenance planning, and improve operational reliability and resource utilization.

Key Outcomes and Cost Savings:

Component	Alerts Identified
Gearbox	23
Main Bearing	10
Generator	25
Total Alerts Identified	**58**

Early fault detection results:

- Minimize turnaround time
- Reduce generation loss
- Extending component life
- Optimize resource and maintenance planning
- Lower replacement and repair costs

Parameter	Benefit Achieved
Generator Bearing Cost Saving	₹ 11 lakhs
Main Bearing Replacement Cost Saving	₹ 120 lakhs
Generator Downtime Reduction/WTG	38 hours
Main Bearing Downtime Reduction/WTG	30 days

Impact and Scalability:

CBM systems are best suited for modern, utility-scale wind turbines (1 MW and above) because they have critical components that are costly to repair, generate valuable real-time data, and where minimising downtime directly improves energy production and reduces maintenance costs.

For further information:

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Best Practice 6: Implementation of Advance Analytics – Predictive Maintenance of Main Bearings

This refers to refers to the deployment of digital analytics software that continuously analyzes operational and performance data from wind turbines and plant equipment. The technology uses real-time data, automated diagnostics, and analytical algorithms to identify performance deviations, predict equipment issues, optimize maintenance activities, and improve overall plant efficiency, reliability, and energy generation.

Problem Statement:

Wind plant operators often face challenges related to limited visibility into asset health, delayed fault identification, and associated generation losses. Persistent abnormalities in critical components, such as elevated main bearing temperatures despite routine maintenance activities, can increase the risk of equipment failure, prolonged downtime, and reduced energy generation, particularly during peak wind operating periods.

Solution Implemented:

An advanced analytics platform was implemented to enable real-time monitoring, early fault detection, and proactive maintenance planning for critical wind turbine components. The system utilizes performance analytics, temperature and vibration monitoring, power curve assessment, yaw and blade pitch analysis, and comparative turbine performance evaluation to identify abnormalities and optimize operational efficiency. The platform also supports generation loss assessment, predictive diagnostics, and faster maintenance response, thereby improving turbine reliability, reducing downtime, and enhancing overall wind plant performance.

Figure 28:Monitoring Dashboard

Key Outcomes:

Parameter	Benefit Achieved
Fault Detection	Early detection prevented catastrophic bearing failure
Energy Generation Improvement	6.8 lakh units during high wind season
Operational Performance	Reduced downtime and optimized turbine performance

Impact and Scalability:

This practice is effective for **small plants** to improve monitoring at low cost, valuable for **large plants** to optimize performance across many turbines, and especially critical for **offshore projects** where predictive alerts reduce expensive mobilization efforts. It can be applied across both onshore and offshore wind farms.

For further information:

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Best Practice 7: Implementation of Bird Guard/Spikes –HT Yard & HT Lines

This technology involves installation of insulated sleeves and bird guards on HT electrical systems to prevent bird contact with live components. It helps reduce bird electrocution, minimize line tripping, improve grid reliability, and support biodiversity protection.

Problem Statement:

Bird interaction with high-tension transmission lines, jumpers, and substation infrastructure can lead to frequent feeder tripping, grid disturbances, and interruption in power evacuation systems. Such incidents result in turbine outages, reduced operational reliability, and increased maintenance requirements, while also posing safety risks to avian species and impacting local biodiversity. Preventive protection measures are therefore essential to improve grid reliability and support environmental sustainability.

Solution Implemented:

Insulated sleeves and bird guards were installed on 33 kV lines, jumper connections, and critical areas near USS yards to minimize bird interaction with energized components. The implementation helps reduce bird electrocution incidents, prevent line tripping, and improve reliability of the power evacuation system.

Key Outcomes

- Minimized feeder trips
- Reduced bird hits, supporting biodiversity
- Lower WTG breakdowns from grid interruptions
- Improved grid stability

Impact and Scalability:

This practice is scalable across small and large wind plants, ensuring reliable grid connectivity. It is equally effective for onshore projects, where bird activity is frequent, and for offshore plants, where grid stability is critical to maintain continuous generation.

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Best Practice 8: Vortex Generator Integration for Wind Turbine Efficiency Improvement

Vortex generators are small aerodynamic devices installed on wind turbine blades. They help control airflow, reduce turbulence, and delay stall, thereby improving blade efficiency and overall turbine performance.

Problem Statement:

Over time, wind turbine blades can experience aerodynamic inefficiencies due to airflow separation, surface wear, turbulence effects, and changing wind conditions, resulting in reduced energy generation and suboptimal turbine performance. These losses are more prominent in turbines operating at low-to-medium wind speed regimes or under turbulent wind conditions.

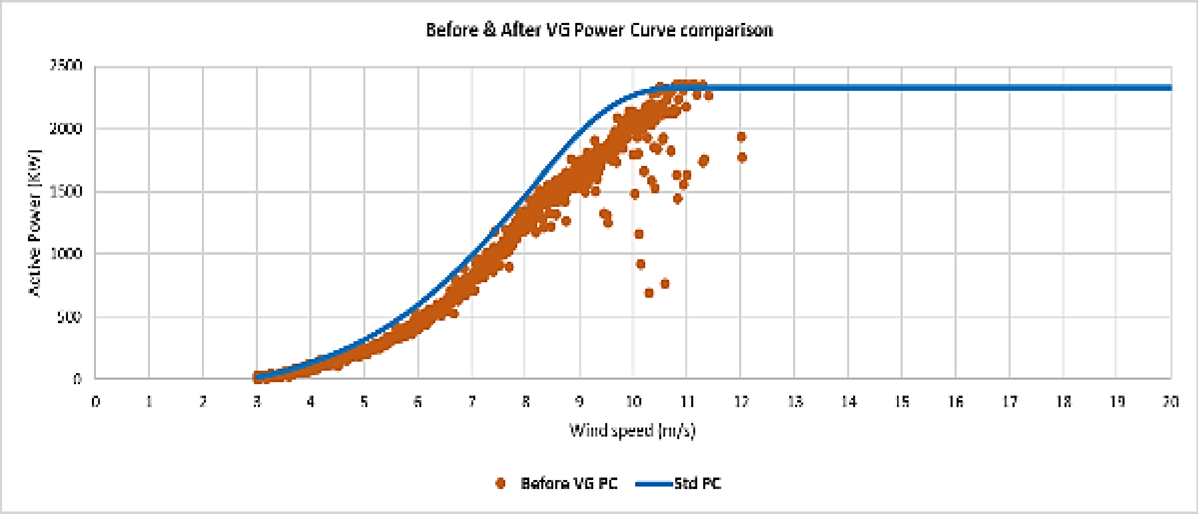

Figure 29: Wind Power Curve before vortex installation

Solution Implemented:

Vortex generators were installed on wind turbine blades to improve airflow distribution and optimize aerodynamic performance. The technology helps minimize aerodynamic losses, enhance blade efficiency, and improve overall turbine performance and energy generation.

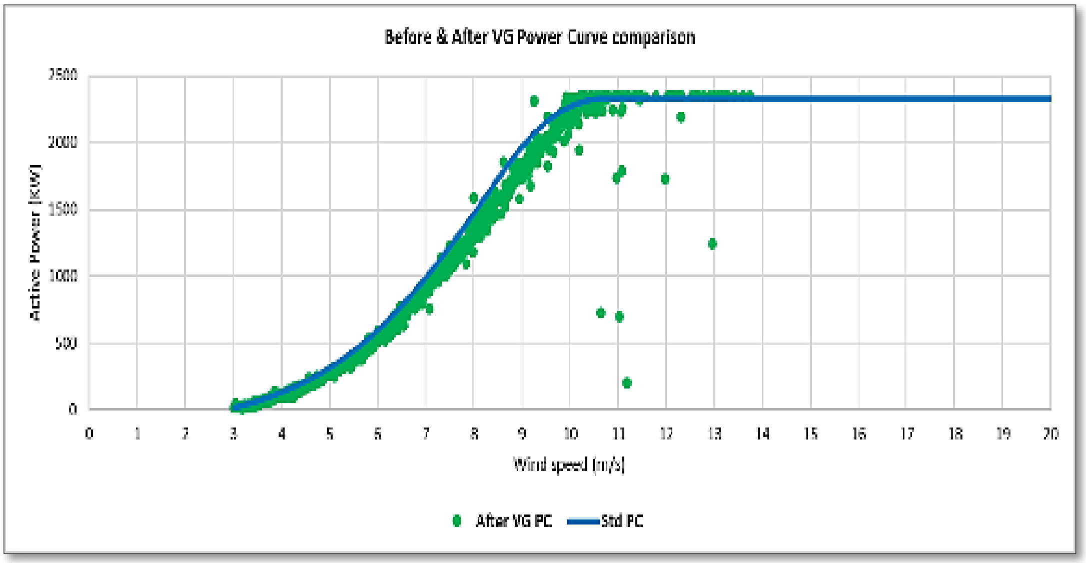

Figure 30:Wind Power Curve after Vortex Installation

Key Outcomes:

Parameter	Improvement Achieved
Annual Energy Generation	Improved by approximately 2–3% across the plant
Cost Optimization	Low-cost retrofit compared to blade replacement or redesign
Blade Life	Extended operational life through reduction in aerodynamic stress
Operational Reliability	Improved reliability and reduced maintenance frequency

Impact and Scalability:

The installation improved energy generation through enhanced aerodynamic efficiency with relatively low implementation cost. The solution is cost-effective and scalable across both small and large wind power plants. It can be implemented in onshore wind projects with easier installation and maintenance accessibility, while offshore applications are also feasible with suitable deployment planning and operational considerations.

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Best Practice 9: Innovative Crane-Less Approach for Pitch Bearing Replacement

Pitch bearings allow blades to rotate for optimal angle adjustment. Traditionally, replacing failed bearings requires large cranes to dismantle the rotor and nacelle. The crane-less method uses specialised up-tower tools and manual handling techniques under controlled low-wind conditions.

Problem Statement:

The WTGs experiences pitch bearing failures due to latent defects. The standard crane-based replacement process are costly and logistically difficult, especially in sites with restricted right-of-way (ROW) for crane movement.

Figure 31: Replacement with Crane

Figure 32: Replacement of WT without crane

Solution Implemented:

A manual crane-less pitch bearing replacement methodology was successfully implemented to eliminate dependency on heavy cranes and reduce maintenance costs. The activity was carefully planned and executed during controlled low-wind conditions to ensure safe handling and operational stability. Prior to execution, all necessary safety and risk management protocols, including HIRA (Hazard Identification and Risk Assessment), JSA (Job Safety Analysis), tool inspection and certification, and vendor competency evaluation, were thoroughly completed to ensure safe and reliable execution of the replacement activity.

Key Outcomes:

Particulars	OEM Crane-Based Replacement	Crane-Less Replacement	Benefit Achieved (Savings of approx.)
Replacement Cost per WTG	₹ 150 Lakhs	₹ 68 Lakhs	₹ 82 Lakhs per WTG (55% reduction)

Table 11: Case for a particular plant

Wind Turbine Generator (Nos)	No. of WTG – Pitch Bearing Failure (Nos)	Replacement Cost – With Crane (150 lakhs/WTG)	Replacement Cost – Without Crane (68 Lakhs/WTG)	Total Savings (Lakhs)
3	3	450	204	246

Impact and Scalability:

This method significantly reduces restoration costs and improves serviceability. It is highly scalable for onshore wind farms of all sizes, especially where crane mobilisation is expensive or impractical. An offshore application is possible but more complex due to marine logistics and stricter safety requirements.

For further information:

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Best Practice 10: Implementation of Human Sky Lifter for Blade Root Maintenance Activities

A specially designed lifting system equipped with enhanced safety features are deployed to safely transport maintenance personnel along with required tools and materials to elevated working locations within the wind turbine. The system incorporates an emergency descent mechanism for safe operation during power failure conditions and has successfully undergone necessary load and safety validation tests to ensure reliable performance during maintenance activities.

Problem Statement:

Cracks in blades and leading-edge protection (LEP) damage are common at wind farms. Standard repair required blade de-erection, which is critical, time-consuming, and kept turbines offline for 7–10 days per blade.

Solution Implemented:

Figure 35: Before- Repairing with Crane

Figure 34: After – Up Tower Repairing

Cracks in wind turbine blades and damage to the leading-edge protection (LEP) system are common issues in wind farms due to continuous exposure to harsh environmental and operating conditions. Conventional repair practices require blade de-erection, which is a critical, time-intensive process resulting in extended turbine downtime of approximately 7–10 days per blade, leading to significant generation loss and increased maintenance costs.

Key Outcomes:

Parameter	Conventional De-Erection Method	Up-Tower Repair Method	Benefit Achieved	Total Saving
Repair Cost per Blade	₹ 8 lakh per blade	₹ 3 lakh per blade	Savings of ₹ 5 lakh per blade	₹ 600 Lakhs savings achieved across 120 blades

- Reduced downtime and faster return to generation.
- Enhanced safety with double-safety winch and certified procedures.

Wind Turbine Generator (Nos)	No. of Blade (Nos)	Cost of De-erection of Blade method (8 Lakhs/Blade)	Cost of Up- tower Repairing method (3 Lakhs/Blade)	Total Savings (Lakhs)
40	120	960	360	600

Impact and Scalability:

The up-tower repair method cut costs by over 60% and reduced downtime significantly. It is highly scalable for both small and large onshore wind farms, where blade damage is frequent. Offshore application is possible but more complex due to marine access and weather constraints, though the method's efficiency makes it attractive if logistics can be managed.

For more Information:

Plant Name/ Group Name	***Contact Person Name***	***Mail ID***
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Confederation of Indian Industry

The Confederation of Indian Industry (CII) works to create and sustain an environment conducive to the development of India, partnering Industry, Government and civil society through advisory and consultative processes. CII is a non-government, not-for-profit, industry-led and industry-managed organisation, with around 9,700 members from the private as well as public sectors, including SMEs and MNCs, and an indirect membership of over 365,000 enterprises from 318 national and regional sectoral industry bodies. For more 130 years, CII has been engaged in shaping India's development journey and works proactively on transforming Indian Industry's engagement in national development. CII charts change by working closely with the Government on policy issues, interfacing with thought leaders, and enhancing efficiency, competitiveness, and business opportunities for industry through a range of specialised services and strategic global linkages. It also provides a platform for consensus-building and networking on key issues. Through its dedicated Centres of Excellence and Industry competitiveness initiatives, promotion of innovation and technology adoption, and partnerships for sustainability, CII plays a transformative part in shaping the future of the nation. Extending its agenda beyond business, CII assists industry to identify and execute corporate citizenship programmes across diverse domains, including affirmative action, livelihoods, diversity management, skill development, empowerment of women, and sustainable development, to name a few. For 2025-26, CII has identified "Accelerating Competitiveness: Globalisation, Inclusivity, Sustainability, Trust" as its theme, prioritising five key pillars. During the year, CII will align its initiatives to drive strategic action aimed at enhancing India's competitiveness by promoting global engagement, inclusive growth, sustainable practices, and a foundation of trust. With 70 offices, including 12 Centres of Excellence, in India, and 9 overseas offices in Australia, Egypt, Germany, Indonesia, Singapore, UAE, UK, and USA, as well as institutional partnerships with about 250 counterpart organisations in almost 100 countries, CII serves as a reference point for Indian industry and the international business community.

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