



2025

Renewathon Project Report

Finding Solution to the dust
settlement problem on solar
plants



Prepared by
New Era

INTRODUCTION

Background:

Solar installations in cement plants help reduce energy costs and minimize greenhouse gas emissions. However, cement dust a byproduct of cement manufacturing creates challenges for these installations. Dust accumulation on solar panels blocks sunlight, reducing efficiency and increasing maintenance needs. The abrasive nature of the dust further complicates cleaning, leading to higher costs and potential panel damage.

Problem Statement:

Cement plants with significant solar installations, like those of Ultratech and NCL, face substantial energy losses due to the accumulation of cement dust on solar panels. Current manual cleaning methods using water and chemicals are labor-intensive, costly, and inefficient. This results in reduced energy generation, lower performance ratios, and significant revenue losses. We seek an innovative, technology-driven solution potentially leveraging electrostatic force or other advanced methods to efficiently remove cement dust and minimize soiling losses.

Objective:

To develop a cost-effective, technology-driven solution that efficiently mitigates cement dust accumulation on solar panels in cement plants. The goal is to minimize soiling losses, enhance energy generation, improve performance ratios, and reduce reliance on labor-intensive, manual cleaning methods. This solution should ensure sustainable, long-term efficiency for solar installations in dust-prone environments.

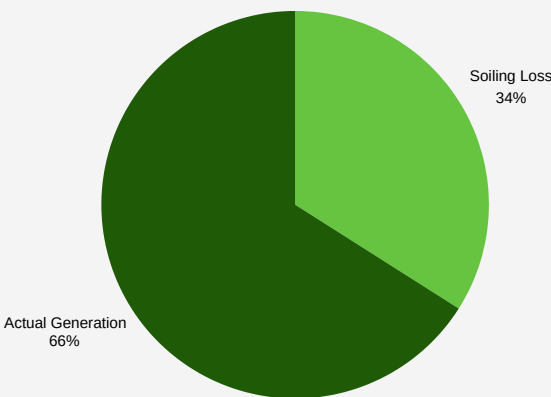
CHALLENGES & IMPACT

Objective:

Cement plants experience significant soiling losses due to the accumulation of cement dust on solar panels. This dust reduces the panels' ability to capture sunlight, lowering energy generation and overall efficiency. Current manual cleaning methods, relying on water and chemicals, are labor-intensive and not fully effective. The resulting performance loss leads to substantial financial impacts, making it crucial to explore innovative, efficient solutions to mitigate soiling losses.

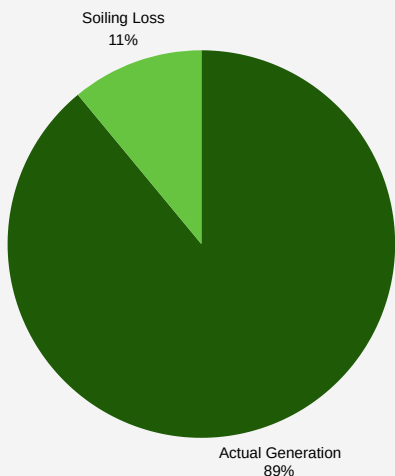
Performance Metrics:

NCL Kondapally:



Generation Loss: 1,22,730 units

NCL Kondapally:



Generation Loss: 4,64,306 units

Expected Performance Ratio	Actual Performance Ratio
61.31%	54.15%
Revenue Loss: ₹4.5 lakhs	

Expected Performance Ratio	Actual Performance Ratio
74.39%	72.70%
Revenue Loss: ₹13.27 lakhs	



CHALLENGES & IMPACT

Current Cleaning Methods:

In cement plants, the most common method to clean solar panels is manual water-based cleaning, occasionally supplemented with chemicals. While these approaches aim to reduce the accumulation of cement dust, they have several limitations:

- **Labor-Intensive and Time-Consuming:**

Manual cleaning requires a significant workforce to clean large-scale solar installations. The need for frequent cleaning cycles—especially in dusty environments like cement plants—further adds to labor costs and demands extensive coordination. In some cases, plants may need to halt operations temporarily for cleaning, disrupting productivity.

- **High Water Consumption:**

Water-based cleaning requires large volumes of water to effectively remove cement dust. Given the increasing focus on water conservation and sustainability, this method can be considered inefficient and unsustainable, especially in regions facing water scarcity. Transporting and storing water for cleaning in remote plant locations can also be logistically challenging.

- **Use of Chemicals:**

Chemicals are occasionally used to enhance the cleaning process, but they bring their own challenges:

- **Environmental Impact:** Runoff from chemical cleaning can lead to soil and water contamination, conflicting with environmental standards.
- **Damage to Panels:** Improper use or overuse of chemicals can degrade the panel's surface, leading to micro-scratches, corrosion, or reduced transparency. This can shorten the lifespan of the panels.
- **Health Hazards:** Chemical exposure can pose health risks to cleaning staff, requiring proper safety measures and protective gear.

Composition of Cement Dust

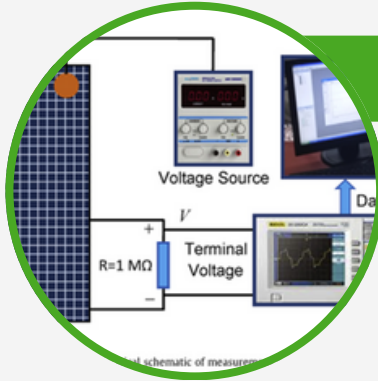
Particle Type/Size	Typical Composition & Adhesion Mechanisms
Fine Dust (<10µm)	<ul style="list-style-type: none">-Electrostatic attraction (small, charged particles)- Van der Waals forces-Light moisture bridging (if humidity is present)
Medium Dust (10–50 µm)	<ul style="list-style-type: none">- Electrostatic attraction- Mechanical interlocking with microscopic panel texture- Partial crusting if damp
Caked / Crusted Dust	<ul style="list-style-type: none">- Chemical binding with alkaline or partially hydrated compounds (CaO, Ca(OH)₂)- Mechanical bonding once hardened- Harder crusts form in high humidity or after repeated wet-dry cycles
Agglomerated Cement Particles (>50 µm)	<ul style="list-style-type: none">- Mechanical lodging in panel frames/edges- Potential to form thick layers if combined with moisture-Typically settle quickly due to larger mass

Key Issues in Cement-Industry PV Environments

Issues	Causes	Impact	Mitigations
Cementation (Crusting) of Dust	Alkaline cement particles (e.g., CaO, Ca(OH) ₂) react with moisture, forming a hardened “cement-like” layer on panels.	<ul style="list-style-type: none">i) Significantly reduces light transmission and energy output.ii) Difficult to remove by simple dry methods; often requires brushing or light water-based cleaning.	<ul style="list-style-type: none">i) Hydrophobic or hydrophilic coatings to prevent dust binding.ii) Surface Acoustic Wave (SAW) vibrations can help crack partially hardened layers if they have not become too thick.iii) Periodic water rinse (manually or via drones/automated sprayers) in severe cases.
Abrasive Wear on Surfaces & Equipment	Cement dust often contains silica or other sharp particles. Repeated contact—whether from wind-blown dust, or mechanical brushing—can slowly erode panel glass, coatings, or cleaning components.	<ul style="list-style-type: none">i) Potential micro-scratches on panel surfaces, reducing efficiency over time.ii) Increased maintenance or replacement needs for brushes, blower nozzles, or robotic parts.	<ul style="list-style-type: none">i) Non-contact cleaning methods (SAW + air blowers) reduce abrasive friction.ii) Use of durable, industrial-grade coatings and cleaning brushes (if employed).iii) Regular inspections to catch early signs of wear or damage.
High Dust Deposition Rates	Proximity to dust-generation points (clinker cooling, raw meal grinding, etc.) leads to rapid buildup on panels.	<ul style="list-style-type: none">i) Frequent cleaning cycles needed to maintain efficiency.ii) Potential for higher O&M costs compared to standard PV plants.	<ul style="list-style-type: none">i) Antistatic coatings to lessen electrostatic attraction.ii) SAW and blower systems operating on a scheduled or on-demand basis.iii) Plant-side measures, such as improved dust collection (baghouses, ESPs) to reduce airborne dust.
Humidity-Driven Accumulation	Water vapor or dew reacts with alkaline particles, forming a sticky or hardened film if not addressed promptly.	<ul style="list-style-type: none">i) Makes dust more difficult to remove, even with electrostatic or vibrational methods.ii) Potential residual streaks or thin films after partial cleaning.	<ul style="list-style-type: none">i) Hydrophobic coatings minimize dust-water interactions.ii) Timed SAW activation (e.g., during early morning dew) to break dust bonding before it fully hardens.iii) Occasional light water rinse or drone spray in problem spots.

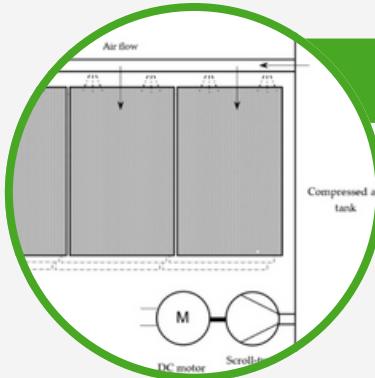


Innovative Cleaning Technologies



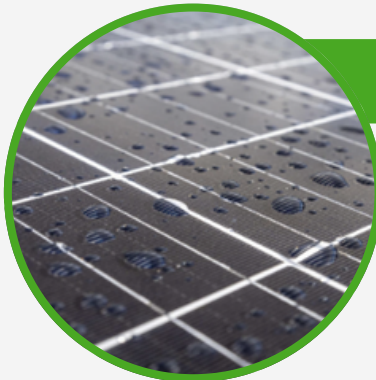
Acoustic waves:

- SAWs are generated by converting electrical signals into mechanical vibrations using interdigital transducers (IDTs) on a piezoelectric substrate
- The waves' mechanical energy interacts with particles or substances on the surface, which can cause movement or dislodgement, enabling SAW-based cleaning and sensing.



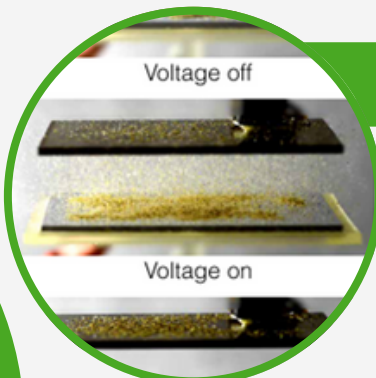
Forced airflow/blower:

- Air blowers are used to create a sweeping airflow across the surface of solar panels to gently lift and remove dust particles.
- This method helps maintain consistent light transmission and PV efficiency without relying on water or mechanical brushes, making it a low-maintenance and water-independent solution.



Coating technologies:

- Coating technologies enhance solar panel performance by addressing key issues like reflection, soiling, and environmental degradation. They achieve this by modifying the surface properties of the panels.
- Types of Coatings: These include anti-reflective coatings, self-cleaning coatings (superhydrophobic and superhydrophilic), and anti-static coatings.



Electrostatic Methods:

- Overall Electrostatic methods utilize electric fields to generate forces that detach and remove dust particles from solar panel surfaces. These methods offer a waterless cleaning solution.
- Types: These methods include Electrodynamical Screen (EDS) and Electrostatic Charge Induction.

Our Hybrid Model - Coating Technology

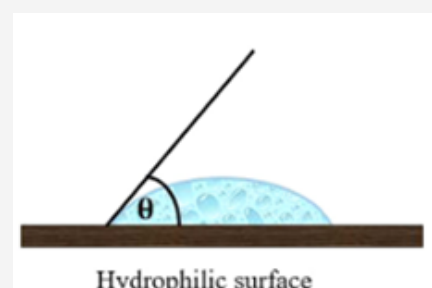
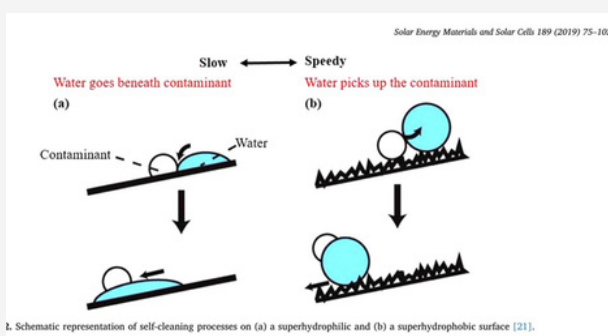
This model is a hybrid cleaning model for solar panels, especially installed in cement plants which includes coatings, Surface Acoustic Waves (SAWs), and air blower systems to address dust accumulation and varying particle sizes. It is a three stage cleaning process which includes

i) **Prevention:** The first chronological consideration to mitigate dust accumulation on surfaces is to apply self-cleaning coatings. These methods in general minimize dust deposition rate or maximize the dust removal rate on the surface of a solar system through natural phenomena such as precipitation, dew, and wind. These methods exhibit significant advantages by preventing dust accumulation without manual labor or energy consumption, and without damaging the PV module surface. These coatings modify the surface properties at the micro or nano level, altering how particles interact with the panel surface and reducing the strength of adhesion forces.

-Hydrophilic : Hydrophilic coatings are essential for solar panels in humid environments due to their ability to facilitate natural cleaning by spreading water evenly across the panel surface. This mechanism leverages environmental moisture, such as rainfall or dew, to reduce manual intervention and water consumption. Hydrophilic coatings like Perma Clean Solar 2 and TiO_2 -based coatings are effective in regions with frequent precipitation, where they help maintain panel efficiency by washing away dust particles. In contrast to hydrophobic coatings, hydrophilic surfaces allow water to spread into thin sheets, creating a self-cleaning effect that is particularly beneficial in coastal and humid areas. By utilizing natural water sources, hydrophilic coatings offer a sustainable and low-maintenance solution for maintaining solar panel efficiency in regions where water-based cleaning is feasible and beneficial.

-Anti-Static Coatings: Antistatic coatings are specialized surface treatments applied to solar panels to combat dust adhesion in high-dust environments like cement plants. These coatings work by neutralizing static charges on the panel surface, effectively preventing electrostatic attraction between dust particles and the solar panel. Typically composed of biodegradable and pH-neutral materials such as ChemiTek's Antistatic Solar Armor (ASA), these coatings are applied using robotic sprayers after an initial cleaning process. While they require annual reapplication due to their 6-12 month durability, antistatic coatings significantly reduce dust adhesion by 60-80%. The benefits of these coatings are multifaceted: they conserve water by reducing the need for frequent water-based cleaning, maintain solar panel efficiency by preventing dust buildup, and decrease operational costs by reducing the frequency of manual cleaning

-Anti-Reflective Coatings: Anti-reflective coatings improve solar panel efficiency by minimizing sunlight loss due to reflection, increasing the amount of light absorbed. These coatings utilize thin-film interference. A thin layer of a material with a specific refractive index, such as silicon dioxide (SiO_2) or titanium dioxide (TiO_2), is applied to the glass surface. The layer's thickness is controlled to achieve destructive interference of reflected light waves. When light reflects from the layer's surfaces, the reflected waves interfere and cancel, reducing reflection. This allows more sunlight to penetrate the solar cell, enhancing energy conversion efficiency.



Our Hybrid Model- SAWs

Chemical bond disruption: this stage includes breaking the bonds between the cement and dust particles, especially of small size. Using Surface Acoustic Waves (SAW) play a crucial role in the hybrid cleaning model as a chemical bond disruption stage. This technology is integrated into the cleaning process to effectively dislodge dust particles from solar panels, particularly in environments where dust forms strong chemical bonds with the panel surface, such as in cement plants.

SAW technology is essential for addressing the challenge of cement dust accumulation on solar panels. Cement dust, when exposed to moisture, undergoes cementation, forming a hard, chemically bonded layer that is difficult to remove using conventional methods. SAW helps break these bonds, facilitating easier removal of dust particles.

Surface Acoustic Wave (SAW) cleaning for solar panels works by using piezoelectric actuators to generate high-frequency vibrations (typically 18-40 kHz) on the panel surface. These vibrations create mechanical stress that disrupts the chemical bonds between dust particles and the glass, weakening the adhesion forces. The vibrations induce oscillations in the dust particles, causing them to detach from the surface when the vibrational forces overcome the adhesion forces. This allows the dust to be more easily removed by gravity or light airflow, improving the panel's efficiency without requiring water or manual scrubbing.

SAW is considered due to its ability to effectively disrupt chemical bonds without the need for water or abrasive materials, which can damage the panels. This method is particularly beneficial in environments where water is scarce or where chemical cleaning agents might be harmful.

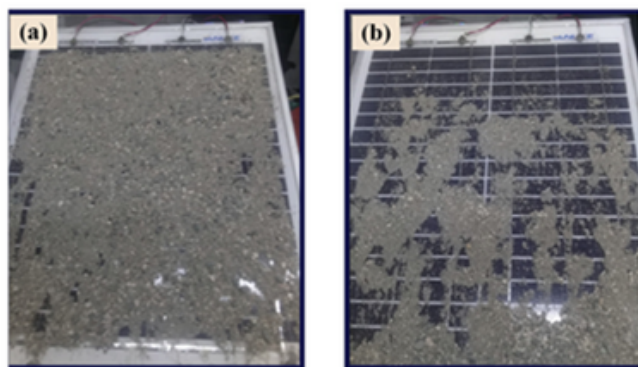


Fig. 11. Pictures of (a) heavily spoiled PV solar panel surface before SAW application and (b) partially cleaned PV panel surface after SAW application.

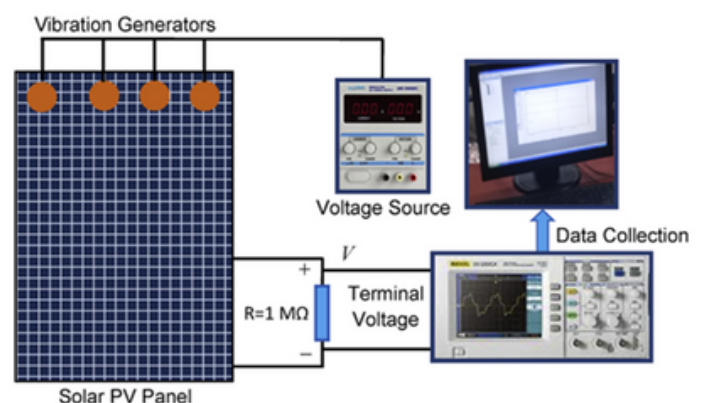


Fig. 8. Electrical schematic of measurement system.

Our Hybrid Model- Air Blower Technology

Air blowers : In solar panel cleaning, various methods are employed to dislodge dust particles, including advanced techniques like surface acoustic waves (SAW) and electrostatic cleaning. However, the effectiveness of these methods relies not only on detaching the dust but also on its complete removal from the panel surface. Ionized air blowers play a crucial role as the final cleaning stage in this process. These systems are essential for ensuring that dust particles, once detached by preceding cleaning methods, are effectively removed, thus restoring optimal panel efficiency.

The working mechanism of ionized air blowers involves a 5 kV ionizer that neutralizes static charges on dust particles. This charge neutralization facilitates easier removal by reducing electrostatic attraction between the dust and the panel surface. Subsequently, a directed airflow, generated at approximately 15 m/s, effectively clears the dislodged particles from the panel surface. Air blowers are particularly effective at removing dislodged larger particles, specifically those greater than 200 μm , utilizing tailored airflow velocities ranging from 5 to 8 m/s.

This approach offers several benefits to solar panel maintenance. It is an energy efficient solution, with standard air blowers consuming only about 0.35 Wh per cycle, while ionized air blowers typically consume 1.2 kWh/day per MW capacity, making it adaptable to diverse climatic zones as a dry-cleaning method. Furthermore, this method reduces soiling losses by approximately 3 to 10%, enhances optical clarity, and ensures sustained energy production with minimal maintenance.




Proposed Model:Autonomous Bot

The proposed hybrid cleaning model for solar panels is implemented as an autonomous bot designed to operate in challenging environments like cement plants. The autonomous solar panel cleaning bot employs a hybrid cleaning mechanism that integrates Surface Acoustic Waves (SAWs) and ionized air blowers to ensure efficient and sustainable cleaning.

The bot begins by positioning itself on a solar panel using navigation systems and control system. The bot uses piezoelectric actuators powered at 6 V DC to generate high frequency vibrations in the range of 18–40 kHz. These vibrations create mechanical stress on the panel surface, disrupting the chemical bonds between dust particles (especially cement dust) and the panel surface. The oscillations weaken adhesion forces, causing fine and strongly adhered particles to detach from the surface. After SAWs loosen the dust particles, the ionized air blower neutralizes static charges on these particles using a 5 kV ionizer. This reduces electrostatic attraction between the dust and the panel surface, facilitating easier removal. A directed airflow with a velocity of approximately 15 m/s clears dislodged particles from the panel surface. The bot autonomously moves across the panel array, repeating the process as needed based on dirt levels detected by onboard sensors.

Operational protocol :

To ensure the optimal performance and longevity of the autonomous solar panel cleaning bot, a comprehensive maintenance and cleaning protocol is essential. This protocol encompasses several key aspects. First, maintenance requirements include periodic inspections every three months to assess component functionality, battery checks and replacements every 6-12 months to maintain power, annual calibration of piezoelectric actuators to ensure optimal vibration frequency around 18-40 kHz for effective dust dislodgement, semi-annual cleaning and inspection of the 5 kV ionizer to guarantee proper charge neutralization for efficient dust removal, quarterly checks and cleaning of the air blower system to maintain the 15 m/s airflow velocity necessary for particle removal, bi-annual calibration of onboard dirt detection sensors to ensure accurate cleaning cycle triggering based on soiling levels, and regular software updates for the navigation and control systems to maintain efficient operation and incorporate improvements. For optimal performance, particularly in environments like cement plants, the cleaning frequency should involve a regular cleaning cycle every 3-4 days to prevent excessive dust accumulation, adaptive cleaning triggered by onboard sensors when dirt levels exceed a predetermined threshold to address varying soiling rates, seasonal adjustments to increase cleaning frequency to every 2 days during dry and dusty seasons to counteract higher dust loads, nighttime cleaning operations to avoid interference with solar energy production and minimize potential thermal stress on the panels and the bot itself, post-rain cleaning within 24 hours of rainfall to remove residual water and grime, and the capability for manual activation for emergency cleaning during sudden dust storms or high pollution events to mitigate the impact of extreme soiling events. Finally, coating durability is a critical consideration, with coatings generally having an expected lifespan of at least 5-7 years under typical Indian climatic conditions, recognizing that environmental factors will influence degradation rates, and their replacement after a particular time period should be factored into long-term maintenance planning. Adhering to this comprehensive protocol will help the autonomous cleaning bot maintain optimal solar panel efficiency by effectively removing dust and other contaminants, while simultaneously minimizing unnecessary wear on the system, with adjustments made as needed based on observed performance and specific environmental conditions to ensure continued effectiveness and reliability.



Key Metrics

Category	Metric	Values	
Technical Effectiveness	Dust Removal Efficiency	95–98%	Combined effect: Coatings reduce adhesion; SAW dislodges particles; blowers remove dislodged dust
	Restoration of Efficiency	80-95%	Combined effect: Coatings reduce adhesion; SAW dislodges particles; blowers remove dislodged dust Near-complete recovery of panel performance when cleaning is integrated
	Humidity Resistance	Excellent	Integrated design mitigates high-humidity impacts (coatings and mechanical cleaning perform reliably)
Economic Viability	Cost per Watt (₹/W)	₹0.30–₹0.50	Incorporates CAPEX for durable coatings, SAW transducers, and blower systems
	Payback Period	5-6 years	Savings in energy recovery and reduced O&M costs lead to a quick payback
	Water Usage (L/MW/year)	0–50 L/MW	Minimal water needed (only for occasional rinsing), compared to high water use in manual cleaning

Key Metrics



Category	Metric	Values	
Sustainability & Safety	Carbon Footprint (kg CO ₂ /MW)	25–45 kg CO ₂ /MW	Lower CO ₂ emissions due to reduced chemical use and efficient, low-power mechanical cleaning
	Chemical Toxicity	None	Uses non-toxic or no chemicals (mechanical and durable coating technologies)
	Worker Safety	Very High	Automation minimizes manual labor and associated safety risks
Operational Feasibility	Dust Load Tolerance (g/m ² /month)	35–40 g/m ² /month	Designed for high dust loads typical in cement plant environments
	Automation Potential	Very High	IoT/sensor integration and robotic control enable autonomous operation
	Maintenance Complexity (hrs/MW/year)	30–40 hrs/MW	Integrated systems reduce labor versus fully manual cleaning, despite having multiple components



Efficiency Recovery & Revenue Impact

Table 2. Application of the Hybrid Model on Cement Plant Case Studies

Case Study	Estimated Performance Ratio (%)	Actual Performance Ratio (%)	Performance Gap (pp)	80% Recovery (pp)	New Performance Ratio (%)	Revenue Loss Before	Revenue Loss After
NCL Kondapally (South Zone)	61.31	54.15	7.16	5.73	$54.15 + 5.73 \approx 59.88$	₹4.5 Lakhs	$₹4.5 \times 0.20 \approx ₹0.9$ Lakhs
UTCL Manikgarh (West Zone)	74.39	72.70	1.69	1.35	$72.70 + 1.35 \approx 74.05$	₹13.27 Lakhs	$₹13.27 \times 0.20 \approx ₹2.65$ Lakhs
Shyam Metallics (East Zone)	65.37	62.74	2.63	2.10	$62.74 + 2.10 \approx 64.84$	₹2.32 Lakhs	$₹2.32 \times 0.20 \approx ₹0.46$ Lakhs

Cost-Benefit Analysis

Table 1. Initial Investment Cost Components

Component	Details	Assumption/Calculation	Cost (₹/MW)	Cost for 5 MW (₹)
Equipment	SAW system + Forced Air Blowers + Coating Applicators	SAW system: ₹8,00,000 Air blower system: ₹3,00,000 Coating applicators: ₹2,00,000	₹13,00,000	₹65,00,000
Installation	Labor & structural modifications (~18% of equipment cost)	$0.18 \times ₹13,00,000 \approx ₹2,34,000$	₹2,34,000	₹11,70,000
Other Costs	Integration & ancillary expenses	Assumed flat rate	₹1,00,000	₹5,00,000
TOTAL			₹16,34,000	₹81,70,000

Cost-Benefit Analysis

Table 2. Application of the Hybrid Model on Cement Plant Case Studies

Cost Component	Details	Assumption/ Calculation	Cost (₹/MW/yr)	Cost for 5 MW/yr (₹)
Energy Consumption	SAW + Air Blower operation	– SAW: $\sim 2 \text{ kW} \times 2 \text{ hr/cleaning} \times 36 \text{ cycles} \approx 144 \text{ kWh}$ – Blowers: $\sim 1 \text{ kW} \times 2 \text{ hr} \times 36 \text{ cycles} \approx 72 \text{ kWh}$ Total $\approx 216 \text{ kWh}$; at ₹6/kWh \approx ₹1,300 (rounded to ₹1,500)	$\sim ₹1,500$	$\sim ₹7,500$
Coating Reapplication	Annual reapplication of durable, non-toxic coatings	Assumed based on market data	₹1,00,000	₹5,00,000
Maintenance	Servicing SAW and blower systems ($\sim 6\%$ of equipment cost)	$0.06 \times ₹13,00,000 \approx ₹78,000$ (rounded to ₹80,000)	₹80,000	₹4,00,000
Subtotal O&M		Sum	$\sim ₹1,81,500$	$\sim ₹9,07,500$
Risk Costs	Warranty & downtime risk ($\sim 10\%$ of project cost per year)	$10\% \text{ of } ₹16,34,000 \approx ₹1,63,400$	₹1,63,400	₹8,17,000
Total Annual Cost		(O&M + Risk Costs)	$\sim ₹3,45,000$	$\sim ₹17,25,000$

Cost-Benefit Analysis

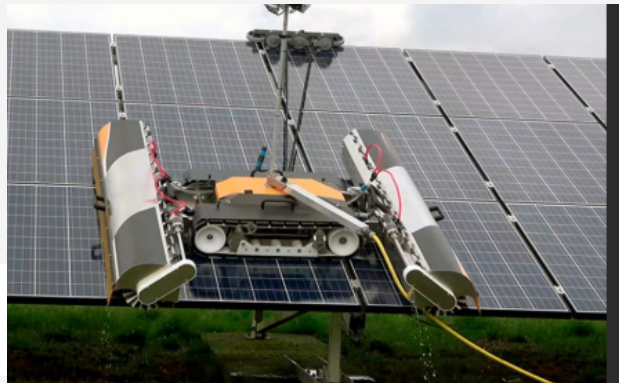
Table 3. Annual Direct Financial Benefits

Benefit Component	Details	Assumption/Calculation	Cost (₹/MW)	Cost for 5 MW (₹)
Energy Recovery	Additional generation from recovered efficiency	122,730 units lost × ₹3.6/unit loss ≈ ₹4,42,000; 80% recovery yields ≈ ₹3,54,000	₹3,54,000	₹17,70,000
Labor Reduction	Savings from reducing manual cleaning cycles	Estimated savings from reduced labor ≈ ₹40,000	₹40,000	₹2,00,000
Water Savings	Avoided costs from high water use in manual cleaning	Assumed saving ≈ ₹36,000	₹36,000	₹1,80,000
Panel Longevity	Extended panel lifespan benefits (reduced degradation and maintenance costs)	Estimated added value ≈ ₹1,00,000	₹1,00,000	₹5,00,000
Total Direct Benefits			₹5,30,000	₹26,50,000

Conclusion

The hybrid solar panel cleaning system, integrating antistatic coatings, surface acoustic waves (SAW), and ionized air blowers, presents a comprehensive solution for addressing dust accumulation challenges in industrial environments like cement plants. This report has demonstrated the effectiveness, practicality, and feasibility of implementing such a system.

The autonomous bot design, integrating SAW and ionized air blowers, provides a scalable and efficient cleaning solution. By leveraging existing technologies and advancements in robotics, this system can be easily integrated into existing PV infrastructure, making it suitable for both new installations and retrofits.



Key Advantages:

1. **Water Conservation:** The system is entirely waterless, aligning with SDG 6 and reducing operational costs.
2. **Chemical Use Reduction:** Eliminates chemical cleaning agents, minimizing environmental toxicity.
3. **Energy Efficiency:** Restores up to 95% of lost power output due to soiling, enhancing solar panel efficiency.
4. **Carbon Footprint Reduction:** Lowers carbon emissions by reducing manual cleaning and water transportation.
5. **Worker Safety:** Reduces manual labor risks associated with rooftop cleaning.
6. **Operational Sustainability:** Designed for long-term operation with minimal maintenance requirements.
7. **Economic Viability:** Offers a payback period of less than three years and a high RO

