

Integrating Robotic Cleaning with Solar Tracker Systems

A Comprehensive Guide

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Executive Summary

The growth of utility-scale solar photovoltaic (PV) plants is accelerating globally, driven by declining costs, improved technologies, and the urgent need for clean energy. These large-scale solar installations are often deployed in high-irradiance regions where sunlight is abundant but environmental conditions—such as dust, sand, and low rainfall—can severely impact system performance. Soiling on PV modules in these areas can lead to energy losses ranging from 10% to 30% annually, directly affecting the financial returns and grid contributions of the solar plant.

To maximize energy harvest throughout the day, most utility-scale solar plants now deploy single-axis tracker systems. Trackers follow the sun's movement from east to west, increasing daily energy yield by 15% to 25% compared to fixed-tilt systems. However, trackers introduce additional design and operational complexity—particularly when integrating cleaning solutions. Safe stow positions, movement synchronization, and system-wide coordination become critical factors when deploying any add-on technology across moving structures.

Robotic dry-cleaning systems have emerged as an efficient, waterless solution for maintaining PV module cleanliness without interrupting generation. These robots operate autonomously or semi-autonomously across PV rows, removing dust without manual intervention or water use. When properly integrated with the tracker system—mechanically and through control logic—robotic cleaners significantly reduce soiling losses, improve plant uptime, and eliminate water consumption. For example, robotic cleaning deployments have demonstrated annual water savings exceeding 66 million litres and have maintained performance on large-scale projects of over 500 MW. The strategic integration of trackers and robotic cleaning systems represents a globally scalable, cost-efficient approach for improving PV plant output, particularly in soiling-prone regions.

About the Author



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Kabeer Kler is Director of Tracker Engineering and Commissioning at GameChange Energy, where he leads global commissioning, O&M development, and tracker optimization.

Since joining in 2021, he has overseen nearly 20 GW of utility-scale projects across the U.S. and international markets, helping bridge regional technical requirements. With an electrical engineering background from the University of Cincinnati, he combines deep technical expertise with field execution.

Outside work, Kabeer is a trained Indian classical musician and plays five instruments.



1. Introduction

Over the past decade, solar energy has rapidly become a cornerstone of the global energy transition. By mid-2024, utility-scale photovoltaic (PV) installations worldwide surpassed 600 GW, propelled by supportive policy frameworks, technological advancements, and the increasing competitiveness of solar in energy markets. With the scale of these deployments comes the growing responsibility to ensure maximum asset performance and long-term operational efficiency.

One of the most significant factors affecting energy yield is soiling—the accumulation of dust, sand, pollen, and other airborne contaminants on the surface of PV modules. In many environments, especially arid and semi-arid regions, this can lead to substantial energy losses if not addressed regularly. While traditional manual cleaning methods remain in use, they are often inefficient, resource-intensive, and unsustainable, particularly in large, remote solar parks where access to water and labor is limited.

Automated robotic dry-cleaning systems are increasingly being adopted to overcome these limitations. These robots can operate autonomously across rows of PV modules, requiring no water and minimal human intervention. However, their successful deployment depends heavily on precise mechanical and software integration with the single-axis tracker infrastructure used in most modern solar plants.



FIGURE 1: Manual Cleaning, Robotic Cleaning

The Genius Tracker system is designed with built-in compatibility for leading robotic cleaning technologies, making integration straightforward and efficient. It meets the alignment, spacing, and docking requirements of top robot manufacturers, and is engineered so that bridges provided by the robot OEM can be easily integrated with the trackers. This design approach enables seamless deployment without the need for costly retrofits. On the control side, it supports standard communication protocols, SCADA integration, safety logic, and testing procedures for seamless coordination between tracker movements and robotic cleaning operations.

With tracker-based PV systems now dominating the utility-scale market, this design ensures that robotic cleaning is not an afterthought but an integral feature of the plant's infrastructure. Field-proven with top robotic cleaning companies, the system enables enhanced plant reliability, sustained high performance over decades, and reduced operational costs. The integration also aligns with long-term sustainability goals by reducing water consumption and minimizing manual maintenance, leading to cleaner panels, higher yields, and improved return on investment.

2. Solar Trackers and Their Role in PV Power Plants

Ground-mounted utility-scale solar PV plants increasingly rely on single-axis tracking systems to optimize energy generation. The trackers rotate PV module rows along a horizontal axis, enabling them to follow the sun's movement from east to west throughout the day. Depending on geographic location and site-specific conditions, according to industry data the system can deliver 15 - 25% greater energy yield compared to fixed-tilt structures.¹ Tracker system consists of long mechanical tables supported by torque tubes, rotating by linear actuators, and coordinated through advanced electronic controllers. In large-scale installations, it is arranged in Central Controller – Node Controller configurations and centrally managed through SCADA systems, allowing for real-time monitoring, precise angle adjustments, and quick fault detection across thousands of tracker rows.

Built for strength and precision, the tracker system offers structural integrity, accurate alignment, and durability to withstand a wide range of environmental conditions. Heavy-duty torque tubes, reliable linear actuators, and optimized mechanical geometry ensure smooth operation and consistent solar capture throughout the day. This robust design not only enhances power generation but also reduces operational interruptions, providing long-term reliability for plant operators.

By integrating advanced control capabilities with proven mechanical engineering, the tracker system forms a dependable foundation for high-performance solar plants. Its design supports rapid installation, scalability, and minimal maintenance requirements, enabling developers and asset owners to achieve superior energy yield, operational efficiency, and cost competitiveness in utility-scale projects.

¹ NREL paper on tracker vs fixed tilt gain including bifacial modules <https://docs.nrel.gov/docs/fy19osti/72039.pdf>

3. Soiling Challenges and Robotic Cleaning Technologies in Utility-Scale Solar PV Plants

Soiling—the accumulation of dust, sand, bird droppings, and other environmental particulates on photovoltaic (PV) module surfaces—is a major cause of performance degradation in solar PV plants, particularly in arid and semi-arid regions. If left unaddressed, soiling typically reduces annual energy yield by 5% to 10% on a global average, though in particularly dusty or arid regions like North Africa and the Middle East these losses can exceed 30% or more. Uneven soiling patterns can further lead to current mismatch, increased thermal loading, and reduced reliability of inverters and other downstream equipment. The industry has traditionally relied on manual cleaning methods involving water, brushes, or compressed air. However, these methods are costly, labor intensive, and unsustainable, especially in remote or water-scarce environments. In high-soiling environments where cleaning is required as frequently as 100 times per year, a single megawatt of installed capacity can require upward of 6,400,000 liters of water and 600 person-hours of manual labor annually under conventional wet-wash methods, making robotic dry-cleaning not just a convenience, but an operational necessity.²

Robotic cleaning technologies offer a compelling solution to these challenges. These systems, particularly the water-free, autonomous variants designed for utility-scale tracker-mounted PV fields, are engineered to perform regular, consistent cleanings without human intervention. Most modern cleaning robots are lightweight (typically under 50 kg), battery-powered, and equipped with dry-brush mechanisms, microfiber rollers, or electrostatic cleaning technologies to remove accumulated dust. Their compact design allows them to navigate across module rows and tilt angles, often aided by the fact that tracker systems level or stow the modules at night—providing an ideal surface for robotic traversal.

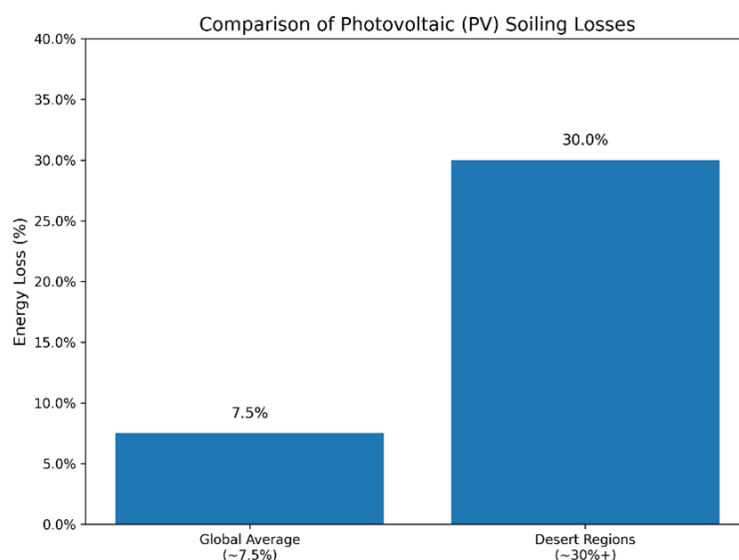


FIGURE 2: Comparison of Photovoltaic (PV) Soiling Losses

² NREL paper on PV soiling losses - <https://docs.nrel.gov/docs/fy21osti/80330.pdf#:~:text=Annual%20losses%20in%20the%20performance%20of%20photovoltaic,humidity%2C%20or%20UV%2C%20making%20removal%20difficult%20%5B44%2C45%5D>

These robots operate autonomously using onboard sensors and pre-programmed paths, often cleaning panels during the night to avoid interference with daytime energy production. This allows for frequent, scheduled cleaning cycles, daily or weekly far exceeding the cadence achievable through manual labor. By maintaining consistent panel cleanliness, robotic systems can recover nearly all the generation losses associated with soiling, which manual cleaning typically restores only intermittently. Additionally, dry-cleaning robots eliminate the need for millions of liters of water that would otherwise be used during each cleaning cycle for a large utility-scale plant, resulting in substantial water conservation benefits.

From an operational standpoint, robotic systems also reduce labor costs, enhance safety by removing the need for human workers to clean at night or in uneven terrain, and provide consistent performance across the plant. Many models feature replaceable brush heads for easy maintenance and offer remote monitoring capabilities, allowing integration with SCADA systems for fault alerts and cleaning cycle tracking. Together, these capabilities make robotic cleaning not just a viable alternative to manual methods, but a key enabler for maximizing energy yield and operational efficiency in large-scale PV installations. Their seamless integration with solar tracker infrastructure further amplifies their value—forming a synergistic relationship that addresses soiling without compromising system integrity or uptime.

4. Importance of Tracker–Robot Integration and Compatibility

The successful deployment of robotic cleaning systems in utility-scale solar PV plants is not solely dependent on the robot's functionality, but also on how well it integrates with the underlying tracker infrastructure. Compatibility between the tracker's mechanical layout and the robot's movement and cleaning mechanism is crucial to ensure reliable, safe, and effective cleaning operations.

The Genius Tracker system is designed to provide a consistent structural pathway for robotic navigation, accommodating robot capabilities through controlled table-to-table transitions that maintain reliable movement and cleaning efficiency without risk to modules or equipment. Trackers are configured to support smooth operation with low slopes in transitions, while mounting hardware, cable management routes, and module frame compatibility are optimized to ensure dependable and efficient robot traversal. Without proper structural support, robots risk falling off or getting damaged. As each added row on the array layout adds one robot and a docking station, GameChange Energy also optimizes project layouts to keep robot count, and subsequently cost, to a minimum.

Moreover, control logic integration is equally important. Robotic cleaning generally occurs during nighttime hours when trackers are in their stow or cleaning position. If the tracker system fails to enter the proper alignment mode (e.g., flat or angled), robots may not be able to operate, risking incomplete cleaning or mechanical failure. Hence, SCADA systems must be configured to coordinate tracker stow logic with robotic cleaning schedules. This requires clear communication protocols, safety interlocks, and fallback conditions in case of faults.

Overall, tracker-robot compatibility is not merely a design convenience but a prerequisite for operational success. Proper mechanical and software-level integration ensures that the cleaning process is reliable, efficient, and minimally disruptive to plant operations.

To streamline this process and ensure all stakeholders are aligned, a robot integration GCS SOP document is available, outlining specifications, interface points, and best practices. By leveraging this SOP during the early design and procurement phases, developers, EPC teams, robot suppliers, tracker OEMs, and SCADA teams can work from a unified framework to achieve seamless, field-proven integration.

5. Integrating Trackers and Robots: Technical Considerations

Successful integration of robotic cleaning systems with solar trackers requires both mechanical and software-level alignment. This section outlines the key technical considerations that ensure reliable and efficient operation.

5.1 Mechanical Integration

Effective mechanical integration ensures that the cleaning robot can move across the solar tracker array without obstruction or damage. This involves aligning the robot's physical dimensions and movement capabilities with the tracker layout, module spacing, tilt angles, and structural tolerances. A well-planned integration minimizes mechanical interference and ensures smooth, reliable operation of both systems.

Mounting Rails

The cleaning robot must be able to traverse the PV array safely and efficiently. This requires compatibility with the mounting structure of the tracker system, ensuring sufficient inter-row clearance and proper support for the robot's movement. In some layouts, additional surface-level rails or tracks may be required to guide wheels or provide stable paths, particularly where structural continuity is essential for reliable operation.



FIGURE 3: Row-to-row bridging

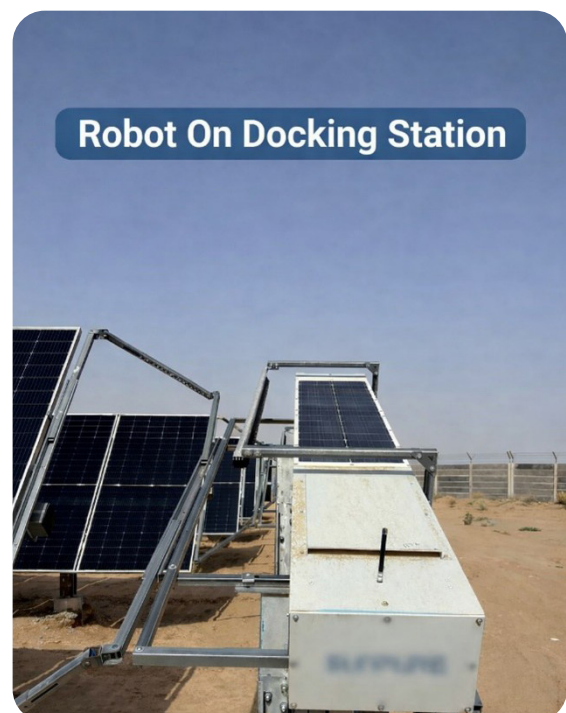


FIGURE 4: Robot on Docking Station

Row-to-Row Movement

Robots should be capable of moving across multiple tracker rows, typically via end-to-end movement across small gaps or inclines. Engineering teams must ensure that tracker row spacing, panel layout, and tilt angles support this movement without obstruction or risk of tipping. This includes checking for height gaps and alignment tolerances between adjacent rows.

Docking and Charging Infrastructure

Most autonomous cleaning robots require a docking station or charging pad. This station must be positioned within the array footprint—usually at the end of a row or on an adjacent structure—and should be accessible without interfering with normal tracker operation. Adequate space, power supply, and secure placement must be ensured during layout planning.

Weight and Structural Load Considerations

The robot's weight typically ranging between 20–50 kg, adds load on the PV modules and tracker structure during cleaning. While trackers are designed to withstand wind and snow loads, teams must validate that the cleaning system does not exert excessive pressure on clamps, torque tubes, or motors. A structural review should be conducted before deployment to confirm load tolerances.

5.2 Control and Software Integration

Software and control integration ensures robots operate only when trackers are safely stationary. Coordinated logic and interlocks prevent conflicts, improve safety, and enable centralized monitoring.

Tracker Controller Coordination

Since trackers operate dynamically throughout the day, robotic cleaning should only occur when the system is stationary typically at night. The Genius trackers can be configured with an overnight stow angle specifically for cleaning operations, after which the system automatically moves to this position once generation hours end. This ensures all rows are in a safe, consistent position for robot deployment without manual intervention, with the tracker controller logic and SCADA or local control consoles coordinating the transition. This automated process streamlines cleaning operations and maintains uniform alignment across the plant.

Communication Compatibility

For coordinated operation, the robot control system can communicate and collect tracker data using open protocols such as Modbus or OPC-UA. The Genius Tracker can provide each tracker node controller's data, such as current table angle, target angle, and more, through the Modbus protocol, enabling easy integration into the robot's operational algorithm via the SCADA network and server. Before initiating cleaning, the robot system should verify that all tracker tables are aligned to the designated cleaning angle, and only then issue the command to start cleaning.

Safety Interlocks

To prevent any mechanical conflict or collision, Genius Trackers are designed to automatically position themselves at the configured cleaning stow angle and remain stationary for the duration of the cleaning operation. In the event of a safety stow trigger such as high wind or snow conditions, the tracker system instantly issues a stow alarm. This signal must be integrated into the robot control logic, ensuring that the robots immediately pause operation and remain idle until the safety stow condition is cleared and the system is ready to resume cleaning.

Compatibility Validation

Before deploying any robotic system, it is essential to confirm structural and electronic compatibility with the Genius Tracker. The Genius Tracker is designed for compatibility with leading robotic cleaning vendors globally, ensuring seamless integration in most utility-scale applications. EPC and O&M teams should still obtain technical approval or certification verifying that the selected robot operates within the tracker's design thresholds. Performing this validation early in the project design phase ensures smooth integration and avoids delays during commissioning.

Monitoring and Diagnostics Integration

Advanced robotic systems can provide detailed diagnostic data such as cleaning completion status, fault alerts, and maintenance requirements. This data can be integrated with the Genius Tracker data to offer unified visibility of both tracker and robot operations. Viewing robotic and tracker status side-by-side enables precise operational planning, faster issue resolution, and more effective O&M decision-making.

In Summary

Soiling remains a significant performance challenge in utility-scale solar — averaging 5% to 10% in annual energy losses globally and exceeding 30% in arid regions — making automated, waterless robotic cleaning systems an increasingly essential operational tool. Their effectiveness, however, depends heavily on precise mechanical and software integration with the tracker infrastructure, with compatibility validation conducted during the design and procurement phase. When properly integrated, these systems have demonstrated the ability to recover nearly all soiling-related generation losses while meaningfully reducing water consumption and manual labor demands.



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