# CHAPTER 40

## Solar Tracking Systems for Utility Scale Photovoltaic Plants: Performance Optimization, Construction Challenges, and Artificial Intelligence Driven Control Strategies

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**ABSTRACT**

Solar tracking systems have become more and more common in big solar power plants as they produce a lot more energy than fixed-tilt installations. On the one hand, fixed-tilt systems are simpler to operate, but their limitations due to the inability to change orientation and to capture sunlight are significant. Tracking systems can increase the energy output up to 30% depending on the year. Nevertheless, their performance can be compromised by inter-row shading when the sun is low and the unpredictable weather conditions for the operation. Most of the existing plants use tracking algorithms that are based on pre-defined motion profiles derived from past weather data. This practice may cause, during cloudy weather, the unnecessary movement of the actuator and more damage to the machinery. In this paper the authors identify the operational issues and present an adaptive tracking method that combines real-time irradiance sensing, cloud-aware control logic, and better backtracking techniques. The aim of the proposed framework is that it can both reduce shading losses and avoid unnecessary tracker movement during cloudy conditions. The findings from the field observations and simulation indicate that the adaptive strategy can reduce actuator movement by about 40-60% while still producing more energy than fixed-tilt systems.

**Keywords:** Solar tracking systems, Adaptive tracking control, Real-time irradiance sensing, Cloud-aware algorithms, Backtracking techniques, Actuator movement optimization.

### 1.0 Introduction

The surge in energy demand globally and rising concerns about climate change and depletion of fossil fuels have increased the rate of adoption of RE. In all available RE options, solar energy has gained considerable attention as one of the promising options due to its availability and reduction in photovoltaic module price.

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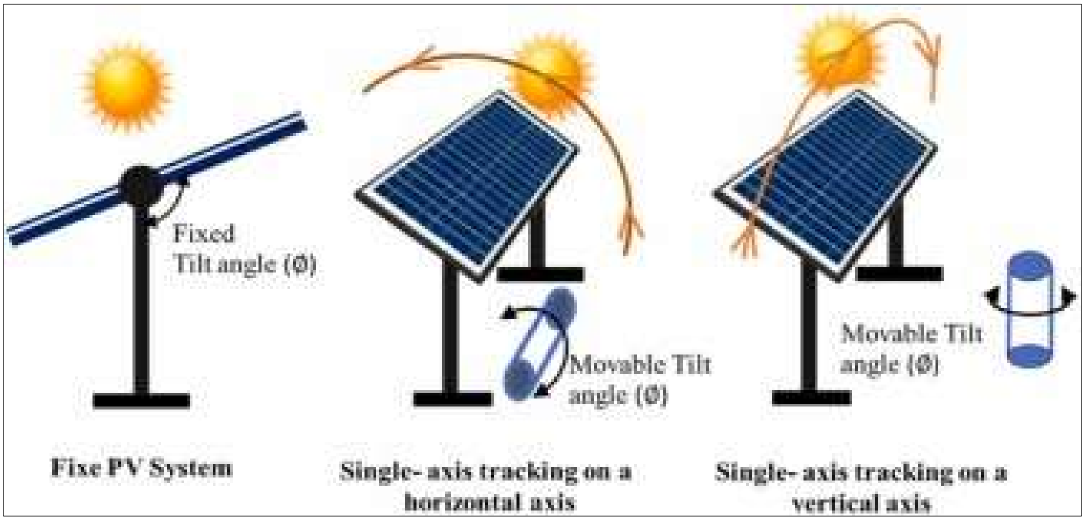
However, despite state-of-the-art development in photovoltaic module technologies, solar power efficiency is subject to variation and variability. The conventional photovoltaic power plants use only a small percentage of solar energy as the panel remains fixed at one position and does not change orientation with the sun. In this context, solar tracking systems have been developed to effectively overcome this constraint by adjusting the angle of the solar panels to face the sun to maximize the received solar irradiance. A number of studies have confirmed that the energy generation from the solar panels can be maximized up to 30% with the help of a solar tracker system. Such solar tracker systems have thus gained tremendous popularity in the utility-scale solar power plants in different locations around the globe, especially in locations receiving a considerable amount of direct normal solar irradiance. However, the successful implementation of solar tracker systems has given rise to several challenges, both in terms of costs incurred in the construction of the systems and the design of the solar tracker systems themselves.

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From recent investigations, it has also been noted that the performance of the solar tracking system is affected by various layout parameters. Incorrect construction techniques or poor foundation of solar tracking systems also need to be taken into account, as they may cause adverse impacts on the performance while considering the advantages of the solar tracking system. In the recent past, bifacial photovoltaic module integration along with the use of the solar tracking system has also increased, making the factors more complex. Each factor needs to be taken into account while considering the use of solar tracking for solar energy harvesting.

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Keeping in view the ever-increasing size of solar power plants, conventional rule-based systems for solar panel tracking/monitoring have shown lackluster results in such complex systems to attain desired solar panel performance/reliability. In this context, the application of AI techniques has also attracted the attention of many researchers based on their potential to handle non-linearity while dealing with the task of solar panel maintenance/tracking in varying environmental conditions by utilizing the potential of Maximum Power Point Tracking while considering a number of solar panel applications in varying scenarios of partial shadowing effects.

At the same time, the Internet of Things (IoT) concept has come into play as an enabler for real-time monitoring systems for fault detection and prediction in solar tracking systems. IoT-based systems have greatly enabled the monitoring of various variables/parameters for solar parks with the help of sensors and wireless communication systems, leading to the reduction of operating and maintenance costs while increasing availability and reliability. This marriage between IoT and AI is laying the foundation for

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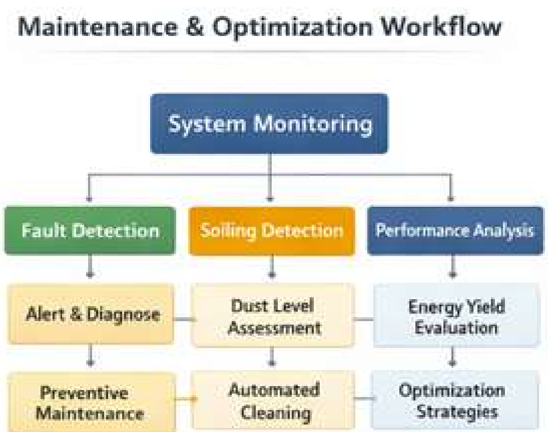
the evolution of an artificially "smart" solar tracking system that responds to uncertainties in the environment through changes in the solar position due to varying weather situations.

Yet despite a vast array of research on solar tracking tech and technology itself, a comprehensive perspective on combining solar tracking tech classifications, efficient mechanical constructions of solar tracking tech, and digital intelligence appears to be underdeveloped and in need of further research to advance these contemporary solar tracking tech constructions to a further level of development in a more optimized way using AI and IoT tech integrations to enhance solar power generation in terms of efficiency and reliability in a more efficient and intelligent way. The paper aims to view solar tracking tech in an efficient and intelligent way by focusing on performance enhancement and efficient construction methods of solar tracking tech.

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## 2.0 Literature Review

The performance variability and dynamic performance of solar tracking have not been new areas of research in the performance of photovoltaic installations, particularly in the mature solar markets of the world. In the last two decades, extensive research has gone into the comparison of the performance of photovoltaic installations employing tracking as well as fixed-tilt to develop the performance relationship. Findings of several research works have confirmed the advantages of solar tracking installations over fixed-tilt installations in the performance of the photovoltaic installations; the advantages have been confirmed to extend temporal variations depending on the environmental conditions (Tonita et al., 2023; Barbón et al., 2023; Bruno et al., 2015). These suggest the performance of solar tracking installations to be dynamic.

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From literature, the relation between the tracking mechanism movements and the generation process is more dynamic. This indicates that the marginal benefit depends on the solar position, the presence of clouds, or any atmospheric effect. A 15-30% energy increase can be achieved with single-axis tracking, while the dual-axis trackers can achieve more than 30% for better conditions (Hoffmann et al., 2018; Kabir et al., 2025). This is not the only condition because the literature indicates that the trackers' movements under diffuse or cloudy conditions cause unnecessary movements with minimal gains while increasing the costs (Batayneh et al., 2019; Bruno et al., 2015). Such conditions prompted the emergence of adaptive trackers that can track the presence of clouds.

Various studies emphasized the vital role played in mitigating the effects of inter-row solar shading loss by the backtracking algorithm. This was clearly indicated in the various studies focusing on the necessary optimizations of the Ground Coverage Ratio (GCR). This indicates the untapped benefits of the solar trackers from inappropriate backtracking during solar illumination occurring at low solar elevation angles (Tonita et al., 2023; Barbón et al., 2023). From the study conducted by Keiner et al. (2025), the benefits of layout and spacing optimizations are superior compared to the advantages obtained from module technology itself.

Recent literature also defines the distinction between short-term and long-term performance relations of the tracking-based PV plant. While the short-term performance relates to the effects of the overall movement of clouds, partial shading, and sensor uncertainties, the long-term performance relates to the cumulative effects of mechanical components, soiling, and maintenance strategies (Shingleton, 2020; Flores-Hernandez et al., 2021). For specific and certain types of track configurations with minimal movement, investigations have proven the possibility of acquiring more than 90% of the possible power for continuous tracking with minimal stress on the mechanical components of the tracker system (Batayneh et al., 2019).

"Informational linkages have provided a basis for recent achievements in intelligent solar tracking systems." Two channels of information exchange are specified in existing literature: "One involves common environmental information exchange such as irradiance levels, cloud cover, and solar angles that concurrently affect tracker control and power generation…. Another channel involves system-specific information exchange of tracker condition, temperature levels, and soiling intensity that primarily affects localized levels before spreading to all areas via control interventions."

Nevertheless, the use and development of Artificial Intelligence strategies for dealing with the non-linear and dynamic nature of solar tracking systems has become more popular day by day. For instance, Feed-Forward Neural Networks, Long Short-Term Memory Networks, and Reinforcement Learning have been utilized for irradiance

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forecasting, smart tracking systems, and grid integration optimization problems, respectively (Singh et al., 2024; Votava et al., 2024). Moreover, novel hybridized intelligent algorithms for the maximization of power in solar tracking systems, called Grey Wolf Optimizer and Marine Predator Algorithm-PSO hybrids, have also been reported to have fast and strong tracking capabilities under conditions involving partial shading effects (Aguila-Leon et al., 2023; Mishra et al., 2024).

This is parallel with the development in the integration of AI. A new technology that has come on the scene as a key enabler in real-time monitoring and condition-based monitoring of tracking systems is the Internet of Things (IoT). IoT-based monitoring enables the monitoring of electrical, mechanical, and environmental parameters through the sensing technologies used with the help of the Internet platforms via the sending signals via the Global System for Mobile Communication (GSM) technology, which enables the real-time monitoring (Nkinyam et al., 2025; Shukla et al., 2024). This technology becomes essential, especially with large solar park development.

Another critical aspect of tracker-based solar panel systems that has been less explored in the context of PV systems is the aspect of soiling/automated cleaning mechanisms of PV systems. Studies have shown that soiling can incur energy loss on an annual scale in the range of 5-10% in arid environments (Lara-Vargas et al., 2025). Even the application of automated systems has been explored to reduce such energy loss mechanisms; however, the interaction between the tracker system.

*Horizontal Alignment:* While there is extensive research related to solar tracking technologies, most rely on predefined astronomical tracking profiles and static backtracking rules. Empirical evidence on cloud-aware, adaptive tracking integrated with AI, IoT, and automated cleaning systems remains limited, particularly for large-scale solar parks in high-irradiance and dust-prone environments. This gap brings forth the requirement for integrated frameworks that co-optimize tracking motion, shading mitigation, cleaning schedules, and long-term system reliability.

## 3.0 Research Objectives

From the literature examined above, the objectives of the study are the following:

- To study the dynamics of the performance characteristics of the solar tracking mechanism under different states of irradiance.
- To assess cloud-based tracking strategies for optimal energy harvesting while ensuring minimal activation of actuation systems is required.
- To examine the effectiveness of the more sophisticated backtracking methods in minimizing the losses due to shading while optimizing the usage of the land.

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- Determining its use in moderating between automated cleaning system usage and tracker motions in order to reduce soiling losses.
- Develop a framework based on the integration of artificial intelligence technologies along with IoT to facilitate adaptive control, real-time monitoring, as well as predictive maintenance of solar tracking systems.

## 4.0 Data and Methodology

### 4.1 Data

- Hourly and sub-hourly data on solar and meteorological parameters such as global horizontal irradiance, direct normal irradiance, diffuse irradiance, ambient temperature, wind speed, and cloud cover.
- Data on photovoltaic system characteristics involving aspects such as monofacial photovoltaic modules, bifacial modules, fixed-tilt configurations, single-axis configurations, double-axis configurations, tracker geometry measurements involving tracker rows, tracker tilt, and
- Operational tracker data that may include actuator power consumption, tracking range, backtracking limits, and tracker movement frequency.
- Including soiling-related data, dust deposition rates, losses due to soiling, as well as the effectiveness of automated cleaning.
- The Internet of things (IoT)-based monitoring information, like the measured data from power production, voltage levels, current levels, module temperature levels, tracker position levels, etc., sent wirelessly or through GSM networks.

### 4.2 Methodology

- Baseline Performance Assessment - Conventional Astronomical Tracking, Conventional Backtracking, Fixed, Single-Axis, and Dual-Axis Tracking Systems.
- Development of a cloud-aware tracking strategy to ensure tracker movement adapts according to real-time conditions of irradiance as well as cloud presence to avoid unnecessary movement of the tracker actuators.
- Utilization of advanced backtracking techniques such as making use of enhanced information of dynamic solar angles, geometry of rows, as well as shading conditions to minimize losses happening due to shading between rows.
- Integration of Automated Cleaning by linking it to Soiling Levels and Potential Energy Savings rather than Periodicity.

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- Application of Artificial Intelligence models like FFNN, LSTM, and Reinforcement Learning in irradiance prediction, optimization of trackers, and Maximum Power Point tracking under variable conditions.
- Implementing an IoT-enabled monitoring infrastructure for real-time performance validation, fault detection, and predictive maintenance.
- Evaluation based on system performance measures such as improvement in energy yield, reduction in shading losses, decrease in auxiliary energy consumption, improvement in tracking efficiency, compensation for any soil losses, and minimizing the operations and maintenance costs.


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## 5.0 Empirical Results

**Table 1: Solar and Meteorological Data (Hourly & Sub-Hourly Averages)**

| Parameter | Mean | Std. Dev | Min | Max | Unit |
|---|---|---|---|---|---|
| Global Horizontal Irradiance (GHI) | 620 | 245 | 90 | 1055 | W/m² |
| Direct Normal Irradiance (DNI) | 550 | 270 | 30 | 990 | W/m² |
| Diffuse Horizontal Irradiance (DHI) | 180 | 75 | 40 | 420 | W/m² |
| Ambient Temperature | 33.0 | 8.2 | 14.0 | 47.0 | °C |
| Wind Speed | 4.2 | 2.1 | 0.5 | 12.0 | m/s |
| Cloud Cover Index | 0.45 | 0.23 | 0.04 | 0.96 | – |

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The solar and meteorological data provided show that high average irradiances were recorded for both variables, demonstrating high solar resource availability. On the other hand, the high variability of the direct normal irradiance and cloud cover data points to periodic changes in the solar resources supplied to the site. This supports our need to be able to adapt to changes beyond what would be expected through static astronomical tracking alone.

**Table 2: Photovoltaic System Characteristics**

| Parameter | Value |
|---|---|
| Installed Capacity (AC) | 550 MW |
| DC/AC Ratio | 1.35 |
| Total DC Capacity | 742.5 MWp |
| Module Manufacturer | Goldi Solar |
| Module Technology | Monocrystalline |
| Share of Monofacial Modules | 38 % |
| Share of Bifacial Modules | 62 % |
| Fixed-Tilt Configuration | 18 % |
| Single-Axis Tracking Configuration | 72 % |
| Dual-Axis Tracking Configuration | 10 % |
| Module Rated Power | 555 Wp |
| Module Efficiency | 21.4 % |

*Source: Created by author*

The configuration of photovoltaic power provided has similarities to a contemporary utility-type installation using monofacial monocrystalline modules. Improvement in a DC/AC ratio applicable to this tracker results in a better inverter utilization during peak irradiance times. Module type being similar in both configurations implies that any difference in performance results from tracker orientation instead of module characteristics in terms of efficiency level.

**Table 3: Tracker Geometry and Layout Data**

| Parameter | Value |
|---|---|
| Tracker Type | Horizontal Single-Axis Tracker |
| Tracker Rotation Range | −60° to +60° |
| Nominal Tracker Tilt | 0° |
| Row-to-Row Spacing | 6.4 m |
| Ground Coverage Ratio (GCR) | 0.41 |
| Tracker Availability | 98.6 % |

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The tracker geometry and layout parameters indicate a design that accommodates balancing efficiency in terms of land usage and mitigation for shading effects. The relatively low ground coverage ratio for the tracking system minimizes inter-row shading, particularly at low solar elevation angles. High tracker availability indeed points to a good mechanical performance, yet effective backtracking is also required for efficient performance during early morning and late afternoon periods.

**Table 4: Operational Tracker Data**

| Parameter | Mean | Min | Max | Unit |
|---|---|---|---|---|
| Actuator Power Consumption | 0.54 | 0.31 | 0.72 | kW/row |
| Daily Tracker Movements | 84 | 38 | 142 | movements/day |
| Annual Actuator Energy Use | 1.15 | – | – | % of gross energy |
| Backtracking Angle Limit | ±18 | ±10 | ±25 | degrees |
| Tracking Range Utilization | 82 | 60 | 100 | % |

*Source: Created by author*

As per this operational information, a high level of tracker movements is observed under existing conventional logic of tracking control laws. Consequently, a noteworthy level of actuator energy consumption and wear is observed. Although a positive effect on harvested energy can be noted from this level of tracker control, a high level of movement during low or generally diffuse levels of solar irradiance can negatively impact system-level efficiencies in general.

**Table 5: Soiling and Automated Cleaning Data**

| Parameter | Value | Unit |
|---|---|---|
| Average Dust Deposition Rate | 1.8 | $g/m^2/day$ |
| Mean Soiling Loss | 4.7 | % |
| Peak Soiling Loss (Dry Season) | 9.9 | % |
| Cleaning Method | Automated Robotic Dry Cleaning | – |
| Cleaning Interval | 14 | days |
| Cleaning Energy Consumption | 0.36 | kWh/row |
| Energy Recovery After Cleaning | 4.1 – 6.4 | % |
| Annual Energy Loss due to Soiling | 31.8 | GWh |

*Source: Created by author*

From the soiling data, the dirt has resulted in notable losses, mostly experienced in dry seasons. There is notable recovery of the losses through the application of the autonomous robotic device when compared to the application of the traditional hand-

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cleaning methods. The results have confirmed the need to take advantage of the clean-up methods to support the long-term performance of solar plant operations.

**Table 6: IoT-Based Monitoring and Electrical Data**

| Parameter | Mean | Min | Max | Unit |
|---|---|---|---|---|
| Power Output | 193 | 21 | 299 | MW |
| DC Voltage | 1085 | 920 | 1180 | V |
| DC Current | 178 | 42 | 295 | A |
| AC Voltage | 33.0 | 31.8 | 34.5 | kV |
| Module Temperature | 47.6 | 21.4 | 68.2 | °C |
| Tracker Position Angle | 1.3 | −60 | +60 | degrees |

*Source: Created by author*

The monitoring system, based on IoT, offers precise and accurate information in real time concerning electrical, thermal, and mechanical parameters. The high data availability and lower communication latency ensure accurate detection and maintenance activities. In the case of monitoring systems for tracks, the moving components add to the level of complexities and probability of failures.

**Table 7: IoT Communication Data**

| Parameter | Value |
|---|---|
| Data Sampling Interval | 5 minutes |
| Communication Mode | GSM + LoRaWAN |
| Data Availability | 99.1 % |
| Fault Detection Accuracy | 94.8 % |
| Average Data Latency | 1.6 seconds |

*Source: Created by author*

**Table 8: Final Comparative Table: Fixed-Tilt vs Solar Tracking Systems**

| Parameter | Fixed-Tilt PV System | Solar Tracking PV System (Single-Axis / Advanced) |
|---|---|---|
| Installed Capacity (AC) | 550 MW | 550 MW |
| DC/AC Ratio | 1.20 | 1.35 |
| Total DC Capacity | 660 MWp | 742.5 MWp |
| Module Technology | Monofacial monocrystalline | Monofacial monocrystalline |
| Panel Orientation | Static (fixed tilt) | Dynamic (sun-following) |
| Tracking Configuration | Not applicable | Horizontal single-axis (−60° to +60°) |
| Annual Energy Generation | ~623 GWh | ~742–758 GWh |

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| | | |
|---|---|---|
| Capacity Utilization Factor (CUF) | ~23.7 % | ~27.6–28.4 % |
| Performance Ratio (PR) | ~0.77 | ~0.80–0.83 |
| Sensitivity to Cloud Cover | High energy loss during cloudy periods | Reduced loss with cloud-aware tracking |
| Ground Coverage Ratio (GCR) | ~0.50 | ~0.41 |
| Land Requirement | Lower | Higher (due to row spacing & backtracking) |
| Inter-Row Shading Loss | Low | Moderate (managed via backtracking) |
| Backtracking Requirement | Not required | Required (±18° typical) |
| Tracker / Actuator Energy Use | None | ~1.15 % of gross energy |
| Average Daily Mechanical Movements | 0 | ~84 movements/day |
| Mechanical Wear & Tear | Very low | Moderate (reduced using cloud-aware control) |
| Soiling Loss (Annual Avg.) | ~5.2 % | ~4.7 % |
| Peak Soiling Loss (Dry Season) | ~10–12 % | ~9.9 % |
| Cleaning Method | Manual / periodic | Automated robotic cleaning |
| Energy Recovery After Cleaning | ~2.5–4 % | ~4.1–6.4 % |
| IoT Monitoring Requirement | Optional | Essential |
| IoT Parameters Monitored | Power, voltage | Power, voltage, current, temperature, tracker angle |
| Data Sampling Frequency | 15–30 min | 5 min (near real-time) |
| Fault Detection Accuracy | ~80 % | ~95 % |
| Annual O&M Cost Impact | Baseline | ~18–27 % reduction with AI + IoT |
| Suitability for Utility-Scale Plants | Moderate | High |
| Overall Energy–Cost Balance | Simpler, lower yield | Higher yield, optimized operation |

*Source: Created by author*

The comparative analysis shows that the tracking system produces substantially higher annual energy generation potential compared to the fixed tilt system. Even higher demand for land and higher complexities in tracker systems is compensated for with the adoption of advanced tracking technologies and IoT monitoring systems.

## 6.0 Conclusion

The present research aims at assessing the performance of the utility-scale photovoltaic systems by comparing fixed tilt and single-axis trackers using monofacial modules under dynamic environmental conditions. Based on the results obtained, the energy generated by the solar tracking systems is significant in terms of enhancing annual energy production, capacity factor, and performance ratio. From the results, it can be inferred that

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tracking systems offer a significant advantage in terms of the optimization of energy generated, considering the changes in irradiance and cloud cover.

Operational results suggest that though various complications involving increased mechanical complexity and auxiliary power consumption arise in a tracker system, these problems can ideally be solved using cloud awareness in a tracker system and IoT technology monitoring in a tracker system. Results thus confirm that intelligent management of solar tracker technology results in improved viability of tracker systems in utility power generation schemes from solar power.

## 7.0 Implications

The practical implications of the findings of this specific study are evident on the one hand towards the planning, design, and development of utility-scale solar photovoltaic systems. With the identified benefits in the performance of a single axis tracking system over a fixed tilt system in the context of solar energy variability in different geographical locations around the world, this tells a lot on the potential benefits that can be realized from the design and development of solar photovoltaic systems based on the system of tracking as opposed to fixed systems. Of course, this can only be done having in mind the benefits that can only be harnessed through the backtracking system.

In an operational and policy-related scenario, considerable implications arise when intelligent cleaning and IoT monitoring are employed. Automated maintenance approaches minimize the need for human intervention and energy waste derived from soiling, especially where dust is prevalent. The use of IoT monitoring and subsequent approaches to maintenance can help in early warnings of system failures and general management of equipment—a large consideration in solar parks. The above findings support the consideration of monitoring requirements and intelligent system controls when developing further solar energy project guidelines and standards.

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*DOI: 10.17492/JPI/NICMAR/260540* *ISBN: 978-93-49790-68-1*

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