Solar Tracking System with IoT

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Publication Date: 2025/11/10

Abstract: Through the integration of mechanical tracking and connected intelligence, IoT-based solar tracking systems can significantly enhance photovoltaic energy capture and enable smarter operations and maintenance. This review covers recent developments in single- and dual-axis trackers, sensor and actuator hardware, and edge-to–cloud IoT stacks supporting real-time telemetry, remote control of devices, as well as predictive maintenance. Both are supported by open source software and cloud computing technologies. In this paper, we compare open-loop astronomical algorithms and AIoT controllers with sensor-driven closed-Loop approaches (e.g, LDR/photodiaode feedback), considering the tradeoffs between point accuracy, "actuation energy", and lifecycle costs. The standard outcome of performance analyses demonstrates that fixed mounts offer an average increase of 15-30% in single-axis performance (with bifacial modules providing additional benefits), while IoT-enabled analytics reduce downtime and enhance O&M efficiency by anomaly detection and targeted interventions. Utility-scale farms, residential off-grid systems, and agri-food applications such as solar-powered drying and cold storage are all possible applications where increased availability directly reduces post-harvest loss. There are still some obstacles to overcome, including mechanical reliability, site-specific economics, and cybersecurity risks caused by networked control.

Keywords: *IoT, Solar Tracking, Photovoltaic Optimization, Edge AI, Predictive Maintenance.*

How to Cite: Saroj Kumar Behera (2025) Solar Tracking System with IoT. *International Journal of Innovative Science and Research Technology*, 10(11), 104-114. https://doi.org/10.38124/ijisrt/25nov108

I. INTRODUCTION

The global decarbonization process has incorporated solar energy, and the optimization of photovoltaic (PV) energy capture is essential for improving electricity cost and system efficiency. The use of solar tracking systems by PV panels to track the sun consistently results in higher annual energy yields compared with fixed-tilted installations, thanks to field-tested modeling and measurements conducted by U.S.". Single-axis trackers provide a 15-25% energy gain, according to research conducted by NREL and its collaborators, making them an economically valuable option for ground-mounted deployments [1].

The Internet of Things (IoT), which combines advancements in cloud platforms, low-cost microcontrollers, and sensing, offers new capabilities to solar-tracking systems, such as remote real-time monitoring and telemetry. for automated fault identification, performance analytics, and adaptive control systems that react to operational and environmental data. Recent experimental prototypes and reviews have shown that IoT-enabled PV monitoring systems enable operators to optimize tracking algorithms, implement predictive maintenance, and minimize downtime based on. weather patterns and historical irradiance, characteristics that, when combined, may enhance the availability and efficiency of energy capture beyond just the advantages of mechanical tracking [2].

Cost-effective hardware (ESP32, Arduino-family boards, LDRs/photodiodes, servo/stepper actuators) is now integrated into real-world implementations with lightweight IoT stacks (MQTT/Blynk/cloud dashboards) and enhanced control (PID, Kalman filtering, or). peer-reviewed and open implementations record tracking RMSEs between 1 and 2°, and hybrid ML methods are used to attain superior pointing precision and noticeable gains in energy output when compared to static panels. IoT-enabled trackers have demonstrated that they can be both affordable and useful for field and research applications, with daily energy boosts in the tens of percent under tested conditions [3].

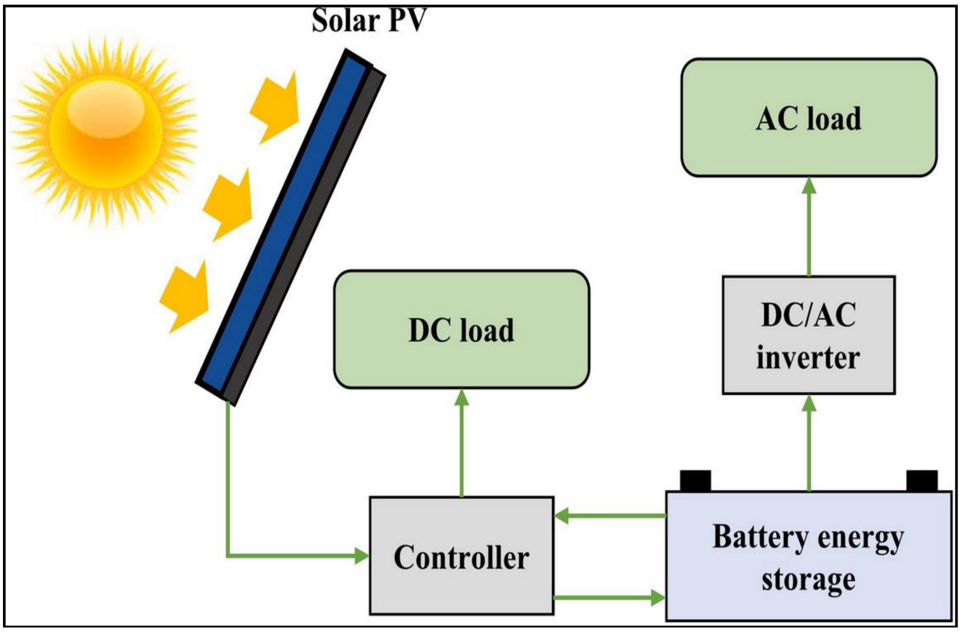

Fig 1 Solar Photovoltaic Technologies

A. Background of Solar Energy Systems.

In recent years, solar PV has experienced a significant surge in usage and is now an integral component of worldwide decarbonization initiatives, with module costs decreasing and policy backing increasing its adoption. PV's swift expansion has transformed generation mixtures in numerous areas, leading to urgent requirements for higher capacity factors, smarter operations, and integration technologies that enhance the effective value of installed capacity [4].

B. The significance of Solar Tracking in Photovoltaic Systems

By mechanically tracking PV modules, solar energy is directed to follow the sun's path, leading to higher energy gains and increased incident irradiance compared to fixed installations. Utility-scale single-axis trackers typically achieve energy gain of approximately 15-25% per year (with dual-axial tracker or more favorable results depending on location conditions and sky conditions). Trackers can enhance performance during peak hours, lower the levelized cost of energy in various scenarios, and better align them with demand profiles, which are all important for achieving improvement in absolute yield [5].

C. The Role of IoT in Modern Energy Systems.

With its ubiquitous connectivity, cloud analytics, real-time performance monitoring, automated fault detection, adaptive control strategies and predictive maintenance capabilities, IoT enables PV systems and trackers to improve availability and operational efficiency at the same time. The use of microcontrollers, telemetry protocols like MQTT, edge analytics, and dashboards can improve the diagnosis of shading issues, actuator faults or sensor drift, while data-driven control and ML improvements can enhance pointing accuracy and reduce downtime in field deployments. This has been reported in recent evaluations on IoT-enabled PV monitoring platforms [6].

D. Objectives of the Study

The main objectives of this review paper are:

- To scrutinize the current state of solar energy systems and highlight the need for maximizing energy yield through effective tracking methods. This involves analyzing the performance of single-axis and dual-axes solar trackers in different environmental conditions.
- To investigate the use of Internet of Things (IoT) technologies in solar tracking systems, emphasizing real-time monitoring, automated control, predictive maintenance, and data-driven optimization to improve system performance and reliability.
- To analyze and evaluate the hardware and software structures of solar tracking systems that are connected to IoT technology, such as sensors, actuators, microcontrollers or communication protocols.
- To identify challenges, limitations, and future research directions in IoT-based solar tracking systems, with a particular emphasis on cost-effectiveness, energy efficiency, and potential applications in industrial, commercial, and food technology sectors.

II. FUNDAMENTALS OF SOLAR TRACKING SYSTEMS

The aim of solar tracking systems is to optimize energy capture and irradiance by positioning photovoltaic (PV) modules near the sun during daylight hours. This makes them ideal mechanical and control solutions. Tracking can be accomplished using either predefined astronomical algorithms or closed-loop sensor feedback, which adjust orientation based on measured irradiance, in fielded systems and research prototypes. Utility-scale and high-performance installations require trackers to achieve levelized cost of energy (LCOE) benefits and better integration with demand profiles [7].

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25nov108

A. Types of Solar Tracking Systems.

There are three main types of solar trackers: fixed-tilt, single-axis, and dual-axial. The latter are for tracking only. Throughout the year, dual-axis trackers and single-axes tracked devices provide elevation control by rotating the panels around the sun's azimuth. This technology keeps solar radiation at bay for many years without disrupting the tracking system. The benefits are influenced by factors such as latitude, project economics, and local climate (such as direct vs. diffuse irradiance), but research studies suggest that the effectiveness of trackers and cost-effectiveness should be considered for each site. [8].

➢ *Single-Axis Trackers.*

The single-axis tracker is the preferred choice for utility-scale PV due to its ability to provide significant energy gains in the 15-30% range while maintaining a balance of mechanical complexity and system costs. Backtracking, torque-limiting, and stow strategies for high winds can optimize single-axical control and combine them with bifacial modules to increase yield and reduce LCOE. Recent large-scale analyses and developer experience indicate that single–axis tracking is the preferred option in many new-install markets due to the tradeoff between yield/cost. [9].

➢ *Dual-Axis Trackers.*

The utilization of dual-axis trackers allows for optimal irradiance capture per panel by keeping the module orthogonal to direct sunlight during both daylight and season. Although the actual energy gains differ depending on the research and location, they are generally within the range of 20% to 40% in favorable locations (particularly significant where the direct beam fraction is substantial) [10].

Table 1 Typical Annual Energy Gain Ranges Vs Fixed Mounting

Mount Type	Typical Annual Energy Gain vs Fixed (%)	Notes / Source
Fixed-tilt	0 (baseline)	—
Single-axis tracker	15 – 30	NREL/market analyses show 15–25% typical; higher with bifacial modules.
Dual-axis tracker	20 – 40	Best for maximizing per-panel yield; higher complexity and cost.

Sources: NREL, MDPI review, PMC study. (NREL Docs)

B. Working Principle of Solar Trackers.

Trackers can operate using either open-loop astronomical control or closed- loop sensor feedback such as photodiodes/LDRs or pyranometers to minimize error in irradiance or panel orientation. The control algorithms available vary from basic two-photodiode differential algorithms to hybrid model-based/ML methods that consider sensor noise, actuator backlash, and wind loading. Low-power stepper motors or linear actuators are commonly used in modern systems to minimize wear while maintaining pointing accuracy, and the trade-off between actuation parasitic consumption and additional harvest is a crucial consideration in their design [11].

C. The Benefits and Drawbacks of Solar Tracking.

The key benefits of tracking are enhanced energy yield, higher capacity factor, and potential LCOE reductions with the right hardware configuration (such as bifacial modules). The constraints consist of increased capital expenditure, more demanding upkeep (mechanical adjustments, bearings, motors), susceptibility to intense gusts of wind and erratic soil movement, and occasionally diminished advantage in highly diffused sky conditions or heavy rainfall. A careful evaluation of insolation features, land expenditure, and operations budgets is essential for determining economic feasibility [12].

III. IOT IS A TERM USED TO DESCRIBE THE USE OF ENERGY SYSTEMS

IoT combines continuous sensing, low-latency telemetry, cloud analytics, and remote control with PV and tracker systems to enable condition monitoring, anomaly detection, data-driven optimization, improved availability, or cost-cutting. Contemporary reviews and experimental deployments have revealed that IoT architecture, along with remote corrective actions or automated storability for shading, inverter faults, or actuator drift, can improve effective up-time and predictive maintenance workflows [13].

A. Overview of IoT Technology.

PV's IoT involves the use of lightweight protocols like MQTT, HTTP, and CoAP to connect edge devices such as microcontrollers, sensors, data loggers or gateways to cloud-based platforms. With the help of edge processing, data can be filtered and pre-aggregated to minimize bandwidth and latency, and cloud services offer users dashboards, long-term storage, fault detection ML models, APIs for integration with asset-management systems. Layers are utilized to expedite O&M response times and enable fleet management scalable across multiple sites. [14].

B. Components of IoT-Based Solar Systems.

➢ *Sensors.*

Irradiance sensors (Pyranometers/Piranoometer(s)/LDRs /Photodiodes) and light sensors for feedback tracking, temperature sensors like LM35 or INA219 with hall-effect sensors as well as environmental sensors such as wind and humidity. For performance analysis and fault detection, high-quality irradiance sensing is superior, while low-cost light sensors are sufficient for closed-loop pointing in many small deployments [15].

➢ *Microcontrollers and Communication Modules.*

From actuator control using small microcontrollers (ESP32, Arduino Nano/Uno) to local analytics powered by SBCs like the Raspberry Pi, edge computation varies. Communications can be based on Wi-Fi, NB-IoT, LoRaWAN

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25nov108

for long-range low-power links, or wired links for utility installations. Throughput, latency, and power/coverage constraints are considered when choosing a protocol for deployment. [16].

➢ *Cloud Platforms and Data Analytics.*

Cloud-based platforms (AWS IoT, Azure IofT), ThingSpeak, Blynk, and custom stacks) offer storage, visualization, ML model hosting, anomaly detection, or predictive maintenance. Research and experiments have demonstrated that cloud analytics, in combination with ML, can predict component degradation and schedule interventions, leading to reduced unplanned downtime and lower maintenance expenses for operators [17].

Table 2 Representative IoT-Driven Operational Benefits Reported in Literature/Case Studies

Benefit Metric	Representative Reported Impact (%)	Source / Note
Reduction in unplanned downtime	35 – 50%	Industry reports and vendor whitepapers on predictive maintenance.
Case study (75 MW) — unplanned downtime reduction	47%	Published project case study reporting 47% drop.
Energy harvest improvement via adaptive control (panel cooling example)	~9.4%	Experimental study showing ≈9.39% improvement.

Sources: industry reviews, case study, experimental paper. (wiot-group.com)

C. *Advantages of Integrating IoT in Solar Tracking*

The advantages multiply when IoT is coupled with tracking: IoT offers performance assurance (real-time telemetry, fault warnings, predictive maintenance), while tracking improves geometric irradiance capture, which leads to increased efficiency. Higher effective energy is collected and less downtime is achieved. New research on AIoT (AI + IoT) enhances adaptive control, such as the ability to adjust tracking strategies. opening avenues for smarter, more robust PV assets by switching between weather forecasts or dynamically trading actuator energy against incremental yield [17].

IV. SOLAR TRACKING SYSTEM ARCHITECTURE BASED ON IOT

A solar tracking architecture based on IoT combines three closely integrated layers—hardware, software (edge and cloud), and control algorithms—to provide precise targeting, real-time telemetry, and remote operation of PV resources. In contemporary utility and distributed installations, the hardware must balance robustness (for wind, dust, and cyclic loading) with minimal parasitic energy for activation, whereas the software must balance robustness with flexibility. Because the software stack manages data acquisition, local pre-processing, secure telemetry, and cloud analytics for fleet management, the integrated architecture places a strong priority on modularity to accommodate sensors, comms, Controllers and modules may be interchanged without requiring a complete system redesign. [18].

A. *Hardware Design*

➢ *Actuators and Solar Panels*

The actuators/drives that realign the PV modules are the focus of the mechanical subsystem. Depending on the needed torque, pointing resolution, weather exposure, and life cycle O&M expenses, the industry generally employs electric linear actuators, geared DC motors, or stepper motors for single-axis trackers. The trade-offs between actuator torque rating and service life in electric actuators for renewable systems are highlighted in reviews (higher torque allows for heavier/larger arrays but raises cost and). actuation energy), and advise using prudent sizing and wind-stow interlocks to ensure resilience. [19].

➢ *Sensors for Light, Temperature, and Position*

Feedback from sensors maintains panel alignment and provides the diagnostics required for IoT analytics. Common arrays contain inclinometers, GPS, and encoders for precise location awareness, pyranometers for accurate irradiance recording, temperature sensors (NTC, RTD, or semiconductor types) for thermal derating experiments, and light sensors (LDRs or photodiodes) for closed-loop pointing. Due to their affordability and robustness, low-cost LDR arrays are frequently employed in prototypes and smaller commercial trackers, while professional monitoring frequently includes a calibrated. pyranometer to determine the actual incident irradiance for performance ratio computations [20].

➢ *Microcontrollers (Arduino, Raspberry Pi, ESP32)*

Options for edge computing include single-board computers (Raspberry Pi) for local data fusion and ultra-low-power microcontrollers (ESP32 family) that integrate Wi-Fi/Bluetooth and deep-sleep modes. or low-power, small-scale ML inference. The ESP32 series is well-liked in solar IoT since it combines connectivity, several ADCs, and low-power modes at a fair price. Raspberry Pi or similar SBCs are selected where more intensive data processing, local databases, or complex gateway functions are necessary, while the package is selected elsewhere. Availability should be a factor in the choice. for remote deployments, there are long-term energy budgets for real-time control requirements and I/O. [21][22].

Table 3 Tracker Adoption (Representative Percentages from Industry & Market Reports)

Metric	Value (%)	Source / note
Share of new U.S. utility-scale PV capacity using single-axis trackers (2022)	94%	Reuters summary of IEA PVPS / LBNL data. (Reuters)
Share of installed U.S. PV systems adopting one-axis tracking (2023, sample metric)	65%	NREL Fall 2024 industry update. (NREL)
Global tracker penetration (2022)	~40%	IEA/market analysis cited in Reuters — expected to rise to ~50% by 2030. (Reuters)

Sources (table): Reuters; NREL.
https://www.reuters.com/business/energy/us-solar-tracker-dominance-offers-learnings-other-markets-2024-08-08/
https://docs.nrel.gov/docs/fy25osti/92257.pdf

B. Software Design

➢ *Data Collection and Processing*

The edge software collects sensor data (analog/digital), filters/transforms it (debounce LDR jitter, apply moving-average irradiance smoothing), and executes safety interlocks (stow on high wind). Using lightweight edge preprocessing, cloud bandwidth is reduced and local fail-safe actions are made possible in near real time (e. g. , restricting movement during gusts). Tried and tested designs employ watchdogs, timestamped packets (NTP/RTC), and circular buffers to assure dependable functionality in isolated locations. Modern scholarly and practical evaluations demonstrate that judicious edge design, particularly timestamp integrity and local buffering, significantly lowers telemetry loss and aids subsequent forensic investigation [23].

➢ *Communication Protocols (Wi-Fi, MQTT, LoRa)*

Depending on the range, power, and network topology, installers select protocols for connectivity: Wi-Fi for high-bandwidth, short-range residential gateways; MQTT as the lightweight publish/subscribe messaging layer for Telemetry in close to real time; and LoRaWAN or NB-IoT for low-power field telemetry over long distances in locations where cellular coverage or private gateways are desirable. The widespread usage of MQTT for IoT messaging, the sub-kbps to tens of kbps profile of LoRaWAN with multi-kilometer coverage, and the cellular-grade coverage of NB-IoT for remote assets are all examples of the options that are highlighted in industry analyses and standards papers. swaps range and power for bandwidth. [24][31][32].

➢ *Cloud Analysis and Storage*

Cloud platforms like AWS IoT Core, Azure IoT, ThingSpeak, open-source MQTT brokers, and bespoke stacks offer long-term storage, dashboards, alarm routing, and ML model hosting for a variety of applications. predictive maintenance. Cloud analytics commonly uses pilot anomaly detection on historical irradiance vs. predicted yield, actuator energy vs. commanded motion, or drift in LDR baselines; Remote alarming that minimizes fault response times and unexpected downtime is demonstrated by the projects. The best practices include encrypting telemetry (TLS), implementing device authentication, and keeping Both raw, high-frequency data (for diagnostic work) and aggregated metrics for trend analytics. [23][34]

C. Solar Tracking Control Algorithms

➢ *Tracking Based on a Light Dependent Resistor (LDR)*

Closed-loop controllers built on LDRs utilize straightforward differential measurements from paired sensors to regulate actuators until light imbalances are minimized; they are inexpensive, durable, and self-calibrating to local atmospheric conditions. While their performance under clear skies is frequently twice as good as that of fixed panels, experimental field research indicates that well-tuned LDR-based systems can provide significant daily energy gains. Under severely diffused sky (cloudy) conditions, performance can deteriorate, and mechanical shielding is necessary to lessen erroneous readings caused by albedo or reflections [20][26].

➢ *Predefined Astronomical Algorithms*

The canonical reference for open-loop astronomical algorithms, which determine the sun's azimuth and elevation from time and geographic coordinates, is the Solar Position Algorithm (SPA) developed by NREL, which has an accuracy of less than 0. 001 degrees. if implemented using the proper time and location inputs. Astronomical tracking is preferred in huge arrays where sensor maintenance would be expensive, in high-precision or concentrator systems, but it necessitates precise RTC/NTP synchronization. as well as a thorough understanding of array geometry and mounting offsets [25].

➢ *Hybrid Strategies*

Combining SPA for rough pointing with LDR or encoder feedback for fine correction, or combining model-based predictions with ML adjustments that adapt to, are examples of hybrid controllers. local atmospheric patterns; such hybrids retain the benefits of accurate sun-angle models while being unaffected by sensor drift and unmodeled shading. Recent research and applied pilot experiments demonstrate that hybrid AIoT approaches can lower pointing RMSE, minimize excessive actuator motions, and, in some instances, increase the amount of net energy collected. as opposed to complete astronomical or sensor control. [26].

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25nov108

V. IOT-BASED SOLAR TRACKING APPLICATIONS

A. Uses in Industry and Commerce

IoT-enabled trackers are used in commercial and utility-scale farms to optimize yearly energy production, balance farm-level stow/load coordination, and facilitate condition-based maintenance across hundreds of tracker rows. According to operator case studies and industry reports, fleet telemetry feeds into O&M dashboards that prioritize bearing or actuator replacements and identify shading occurrences at the string level. The quick uptake of single-axis trackers in big projects is driven by the fact that combining monitoring gear with telemetry and predictive maintenance lowers the LCOE and minimizes unanticipated downtime [18][30].

B. Home Solar Installations

IoT monitoring (usually using local Wi-Fi + MQTT or vendor cloud APIs) allows owners and installers module- or inverter-level visibility for homes and small commercial rooftops. Although trackers are less prevalent on roofs due to weight and clearance constraints, IoT telemetry is beneficial for controlling small tracker prototypes and pole-mounted micro-PV for off-grid loads. battery charging, alerts for implement maintenance, and adapting pointing schedules to local occupancy/consumption patterns—all of which enhance self-consumption and reliability. [22][6].

C. Integration in Food Technology

➢ *Food Processing Facilities Run by Solar Power*

Solar dryers, conduction dryers, and compact solar thermal devices are well-known technologies for drying fruits, vegetables, and fish, which increases product quality and lowers post-harvest losses in this sector. IoT integration (temperature/humidity logging, solar resource telemetry) enables processors to optimize drying cycles, identify anomalies, and plan batch operations for areas without access to consistent grid electricity. According to FAO project studies on solar drying, matching peak solar windows improves output and product consistency. [27].

➢ *IoT Energy Management and Cold Storage*

Solar-powered cold storage is a quickly developing use case where IoT monitoring and control are crucial. Companies like ColdHubs provide solar walk-in cold rooms with: Remote telemetry to manage battery/inverter loads, arrange demand response to reduce diesel generator runtime, and maintain temperature setpoints. The impact and case studies demonstrate that combining Solar energy coupled with remote monitoring reduces food spoilage, increases shelf life (for example, from days to weeks), and facilitates pay-as-you-store business models that help small farmers. and regional markets. IoT facilitates predictive alerts (such as battery weakness or compressor faults) that significantly lower food loss if operators respond promptly. [28][29].

Table 4 Communication Protocols: Typical Data Rates, Ranges and Recent Adoption Figures

Protocol	Typical data rate	Typical range (line-of-sight)	Reported adoption / market metric (%)	Source
MQTT (messaging)	Lightweight messaging (payload small; broker overhead small)	N/A (runs over IP)	MQTT used/essential in ~50–55% of IIoT projects (survey).	HiveMQ survey (2022). (hivemq.com)
LoRaWAN	0.3 kbps – 50 kbps (typ.)	Kilometres (2–15 km typical rural LOS)	LoRa market share ~36% of LPWAN (projected / regional varies).	LoRa Alliance / IoT Analytics. (LoRa Alliance®)
NB-IoT	Up to ~100–250 kbps (implementation dependent)	Cellular coverage (wide)	NB-IoT ~20% (ex-China LPWAN share) / large share in China; projections rising.	GSMA / IoT Analytics. (GSMA)

Sources (table): HiveMQ; LoRa Alliance; IoT-Analytics; GSMA.
https://www.hivemq.com/blog/2022-survey-shows-mqtt-adoption-is-high-for-industry/
https://lora-alliance.org/wp-content/uploads/2020/11/lorawan_regional_parameters_v1.0.3reva_0.pdf
https://iot-analytics.com/lpwan-market/
https://www.gsma.com/iot/

VI. PERFORMANCE EVALUATION AND OPTIMIZATION

Tracker gains differ depending on latitude, DNI, module type, and system configuration, necessitating both field data and modeled projections when comparing PV systems with fixed-tilt references. In general, single-axis trackers can increase annual energy yield by around 15-25% over fixed-tilt systems, as demonstrated by broad syntheses and field validation studies. Alternatively, pairing single–axill tracker with bifacial modules typically adds an extra 4-15% (site dependent), while dual-axial trackERS sometimes offer larger gains per panel in direct-to-unclimated climate[citation] but require more complexity and cost. These ranges are supported by NREL model/validation work and national-scale industry reports that quantify tracker yield and provide economic justification for tracking. [35].

Table 5 Typical Performance / Economic Impacts of Tracking vs Fixed

Metric	Typical value (range)	Note / source
Single-axis energy gain vs fixed	15% – 25%	NREL modeled & validated ranges. (NREL)
Bifacial + tracker additional gain	4% – 15%	Bifacial rear-side contributions depend on ground albedo. (NREL)
Dual-axis energy gain vs fixed	20% – 40% (site dependent)	Best in high-DNI sites but higher cost. (ScienceDirect)
Reported LCOE reduction (tracker + bifacial)	≈16% (example study)	Market/IEA syntheses reported in Reuters summary. (Reuters)

Sources: NREL; industry/press synthesis.
https://docs.nrel.gov/docs/fy19osti/72039.pdf

It's important to differentiate between immediate module-level efficiency (intrinsic cell/module conversion) and system-specific energy yield (kWh produced over time) when assessing efficiency versus fixed systems. The increased incident irradiance of trackers results in higher energy yield and capacity factor, rather than improved conversion efficiency at the cell level. Multiple utility studies indicate that single-axis tracking can increase generation-weighted capacity factors by several percentage points in warmer areas, resulting in improved efficiency and lower LCOE over the lifetime of their projects. Utility-scale market analyses and DOE/NREL cost benchmark reports lend support to these observations [36].

A. *Efficiency Comparison with Fixed Systems.*

Both direct comparative experiments and large-sample modeling demonstrate that tracker performance is influenced by local solar resource characteristics and system design choices, such as module tilt, spacing, bifaciality, row-height, etc. When in clear skies, trackers can recover most of the extra energy they need. In diffuse climates, the benefit decreases while fixed mount systems may be preferred due to their location sensitivity. Economic analyses connect energy gains to capex/O&M differentials, leading to the identification of single-axis trackers as more cost-effective in certain scenarios where high soil density and low DNI are prevalent [37].

B. *Energy Yield Improvement.*

The field trials and system-level simulations demonstrate that trackers offer more than just raw percentage gains, as they also enhance energy production distribution throughout the day by reducing morning/evening drop-offs, shifting some output to higher-value hours, and improving compatibility with diurnal demand. By pairing trackers with bifacial modules, the rear-side gains of 10-15% in favorable tests are known to increase the cumulative yield. It is possible to calculate the payback by adding multiple extra MWh per year installed, which is a significant measure. Empirical and academic validations offer empirical comparisons of the effects of tracking on hourly yield curve changes and annual totals, based on several NREL and other studies [35][38].

C. *IoT-Based Predictive Maintenance.*

Predictive maintenance (PdM) through IoT telemetry, which involves monitoring actuator current, encoder positions, ambient sensors and inverter/string metrics, can identify degradation patterns before failure. Unplanned downtime is reported to have been significantly reduced in industry case studies and pilot projects, with one example of such reductions being a reported 75 percent. The MW case study and the vendor/industry claims of 25-70% declines in various O&M metrics are subject to change based on fleet size and analytics maturity. Maintenance costs are reduced through the use of PdM, which allows for targeted bearing/actuator swaps and reduces unnecessary scheduled visits. Depending on the operator and the level of sophistication of fault prediction models, the sensitivity results are diverse [39][40].

Table 6 Representative Predictive-Maintenance Impacts Reported

Metric	Representative improvement (%)	Source / note
Reduction in unplanned downtime (case study)	47%	75 MW project case study. (IJFMR)
Maintenance cost reduction (industry claims)	25% – 35%	Vendor/industry reports on AI-driven PdM. (EasySolar)
Reported ROI (some PdM pilots)	hundreds of % (project dependent)	Vendor case studies report high ROI in specific deployments. (gembo.co)

Sources: case studies / industry reports.
https://www.ijfmr.com/papers/2024/6/30731.pdf

D. *Optimization Techniques*

The optimization process encompasses control-level enhancements like improved pointing algorithms and movement scheduling, as well as system-wide trade-offs such as actuation energy or incremental generation. The latest techniques comprise fast edge filtering, solar position algorithms for coarse pointing, and machine-learning models for fine adjustment or anomaly detection; they also employ schedule moves to prevent frequent small actuations that heighten wear. Investigations using ML/hybrid controllers

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25nov108

reveal reduced RMSE and less unnecessary cycles of actuators than with the traditional naive control, leading to improvements in lifecycle economics [41][42].

- *Machine Learning for Tracking Accuracy*

Cloud-based irradiance changes, sensor correction, and actuation scheduling optimization have been achieved through the use of machine learning (ML) and deep learning strategies. In certain settings, ML can minimize pointing errors and accurately predict irradiance transients than static heuristics. Empirical evidence indicates this is achievable; controllers that use distributed local programming (such as micro-climate and shading dynamics) can learn intricate local patterns to optimize control by optimizing for actuation expenses. The benefits of data quality and model generalizability vary, with some indicating an improvement in RMSE, others suggesting an increase in false stows or modest improvements in net energy [43][44].

- *Adaptive Control Systems.*

By utilizing weather forecasts, energy price signals (where available), and battery/storage state, adaptive control can be used to determine the aggressive tracking and its intensity. Active tracking in clear conditions is the preferred method of adaptive strategies, which can reduce actuator motion to conserve parasitic energy. By combining deterministic sun-position models with sensor/ML corrections, hybrid strategies have been found to offer near-astronomical pointing accuracy and resilience against sensor faults and localized shading, which are now widely used in pilot applications. This AIoT approach is adaptive and provides support for fleet-level optimization, which involves managing row–to–row interactions (mutual shading) [41][45].

VII. CHALLENGES AND LIMITATIONS

A. Technical Challenges.

Moving parts, such as bearings and actuatorntae, or gearboxes (of which trackers are technically aware) are subject to periodic maintenance but are also susceptible to wind loading and soil settlement. As per the literature, sensors such as LDR baseline shift, pyranometer calibration loss, actuator backlash, and encoder failures are frequent field issues. Additionally (actuation) requires parasitic energy to balance against incremental harvest. Unreliable IoT telemetry is made more difficult by the connectivity/BT battery limitations of off-grid sites, which can lead to wear and tear caused by harsh conditions such as sand, salt, and high temperatures. Early-life failure modes are frequently influenced by mechanical and sensor realities that necessitate conservative design and PdM to manage them [35][19].

B. Economic Considerations.

The higher upfront capex for trackers and O&M risk premia is a financial issue. In utility contexts, the use of trackers can lead to a decrease in LCOE by increasing yield and capacity factor, but economic factors such as land cost, module pricing (e.g: bio-capacitor/modify), local labor or O&M costs, and financing terms are subject to change with respect to site and scale payback timelines. Project-level capex comparisons are facilitated by DOE/NREL benchmark data and ATB cost modeling, which demonstrate the importance of conducting up-front sensitivity analysis when module and tracker prices change rapidly [36][37].

C. Data Security and IoT Vulnerabilities.

IoT integration provides significant operational advantages, but it also introduces novel attack foci. Newly published security research and vulnerability disclosures have exposed internet-exposed solar inverters, cloud management APIs, and fleet control systems to serious vulnerabilities that could allow remote manipulation of inverteder setpoints or mass shutdown operations. Thousands of vulnerable devices and high-severity vulnerabilities have been documented by firms and researchers, and threat modeling studies using STRIDE highlight risks across sensors, gateways, cloud layers, etc. IoT-enabled trackers may create systemic risk vectors if the asset is not managed through the use of device hardening, network isolation, TLS authentication processes, secure firmware update processes and regulatory attention [46][47][48][49].

VIII. FUTURE SCOPE

By utilizing lightweight ML models at the edge, AIoT and edge intelligence will soon merge to enable rapid response to sudden changes in solar radiation levels. This approach involves embedding lightweight MCUs or small SBC's at various locations across networks with low power connections. Additionally, they aim to reduce cloud dependence and speed up tracking decisions. Edge-AI techniques reduce telemetry expenses and latency, making it possible to create more autonomous and durable trackers for off-grid and rural electrification initiatives. Current research indicates that edge inference can enhance responsiveness and energy capture by combining astronomical observation with sensor feedback [51][52].

Trackers are tightly linked with distributed storage, smart inverter, and demand-side controls, which allows for optimal tracking based on battery state, time-of–use prices, or grid signals, making system-level integration an important growth vector that goes beyond per-module control. In agricultural/food-processing facilities with critical load profiles and cold-chain needs, microgrid resilience can be improved by adopting value-aware tracking practices such as more aggressive tracking when the marginal electricity value is high or reducing actuation when storage can reduce peak demand. A diverse research and deployment landscape is emerging due to the rising tracker penetration and parallel growth in storage and fleet orchestration services, as indicated by market forecasts and industry outlooks [53][54].

High-accuracy astronomical models can be combined with self–calibrating sensor arrays (LDRs, photodiodes, encoders), satellite/nowcast weather feeds and reinforcement-learning controllers that adapt to local microclimate conditions and soiling patterns for advanced hybrid control, which is also a promising area. By optimizing mechanical life cycles, these hybrid systems can minimize unnecessary actuator cycles and provide dynamic performance improvements through dynamic bifacial gains. They can also

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25nov108

be combined with IoT-driven predictive maintenance to prioritize parts that may fail later. Research and policy will prioritize establishing standards for data exchange, telemetry schemas, and secure over-the-air updates to ensure safe deployments [51][55].

IX. CONCUSION

The field of IoT-enabled solar tracking is a mature but rapidly evolving solution space. Trackers offer site-dependent energy gains through fixed mounts, while IOT layers provide operational intelligence for scale-up benefits through monitoring, remote diagnostics and PdM workflow methods. The integration of AI and edge processing enables systems to better cope with weather variability and reduce their dependence on continuous cloud connectivity, leading to improved uptime and energy capture in utility and off-grid settings. Nonetheless, comprehending this possibility necessitates meticulous techno-economic analysis for every site to ensure that capex/O&M tradeoffs remain advantageous.

The gains of IoT and AI are accompanied by systemic duties, such as cybersecurity, supply-chain transparency, and robust device management, as trackers and inverters can be easily controlled across networks. Recent disclosures of vulnerabilities and investigative reporting highlight the importance of implementing stricter device onboarding practices, incident-response playbooks, and safeguarding asset owners against manipulation through unsecured or undocumented interface issues. Control algorithms will be best suited for applications in economics, food-chain management, and lifecycle O&M models that factor in PdM ROI through interdisciplinary work.

IoT-based solar tracking has a broad and practical future, with incremental technical advancements like edge AI, sensor fusion or hybrid control, system integration of storage, smart inverter technology, and secure, standards-driven deployments that maximize the benefits of trackers. To ensure safety and affordability, it is essential to conduct a thorough investigation, provide policy advice, and share industry best practices when scaling these systems.

REFERENCES

[1]. S. A. Pelaez, C. Deline, P. Greenberg, J. Stein, R. K. Kostuk, "Model and Validation of Single-Axis Tracking with Bifacial Photovoltaics," National Renewable Energy Laboratory (NREL) preprint, 2018. Available: https://docs.nrel.gov/docs/fy19osti/72039.pdf

[2]. "Smart Monitoring of Photovoltaic Energy Systems: An IoT-Based Prototype Approach," Article 100134, Scientific African / ScienceDirect (in press 2025). DOI: 10.1016/j.grets.2024.100134. Available: https://www.sciencedirect.com/science/article/pii/S2468227625004430

[3]. M. A. Al-Sheikh, "IoT-Enabled Dual-Axis Solar Tracking System Using ESP32 and Blynk for Real-Time Monitoring and Energy Optimization," Jupiter Publikasi Ilmu Keteknikan, Jan 2025. DOI: 10.61132/jupiter.v3i1.695. Available: https://www.researchgate.net/publication/388106720_IoT-Enabled_Dual-Axis_Solar_Tracking_System_Using_ESP32_and_Blynk_for_Real-Time_Monitoring_and_Energy_Optimization

[4]. International Energy Agency (IEA), "Solar - IEA," IEA, 2024. Available: https://www.iea.org/energy-system/renewables/solar-pv

[5]. S. A. Pelaez, C. Deline, P. Greenberg, J. Stein, R. K. Kostuk, "Model and Validation of Single-Axis Tracking with Bifacial Photovoltaics," National Renewable Energy Laboratory (NREL) Preprint, 2018. Available: https://docs.nrel.gov/docs/fy19osti/72039.pdf

[6]. V. Rawat, "An Evaluation of IoT-Based Solar Panel Monitoring Systems," E3S Web of Conferences (ICPeS 2024 proceedings), 2024. Available: https://www.e3s-conferences.org/articles/e3sconf/pdf/2024/70/e3sconf_icpes2024_08005.pdf

[7]. K. Anderson, "Single-Axis Tracker Control Optimization Potential for the Contiguous United States," National Renewable Energy Laboratory (NREL), Preprint NREL/CP-5K00-82811, July 2022. Available: https://www.nrel.gov/docs/fy22osti/82811.pdf

[8]. R. Sadeghi et al., "A Review and Comparative Analysis of Solar Tracking," Energies, 2025. Available: https://www.mdpi.com/1996-1073/18/10/2553

[9]. NREL, "Utility-Scale PV | Electricity | 2024 ATB," NREL ATB web page (2024). Available: https://atb.nrel.gov/electricity/2024/utility-scale_pv
Also: "US solar tracker dominance offers learnings for other markets," Reuters, Aug 8, 2024. Available: https://www.reuters.com/business/energy/us-solar-tracker-dominance-offers-learnings-other-markets-2024-08-08/

[10]. [K.R. Oyshei et al., "Comparative analysis of solar module configuration and tracking," PMC (2024). Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC11283007/
Also: L. Burnham et al., "Performance of Bifacial PV Modules on a Dual-Axis Tracker," PVSC study (2025). Available: (see linked study in text)

[11]. "Internet of Things-Based Solar Tracker System," ResearchGate chapter (IoT tracker design), 2019. Available: https://www.researchgate.net/publication/351114059_Internet_of_Things-Based_Solar_Tracker_System
Arduino Project Hub, IoT tracker examples: https://create.arduino.cc/projecthub

[12]. "Advantages and disadvantages of a solar tracker system," SolarPowerWorld, May 9, 2016. Available: https://www.solarpowerworldonline.com/2016/05/advantages-disadvantages-solar-tracker-system/
Also: NREL feasibility study, 2013: https://www.nrel.gov/docs/fy13osti/57251.pdf

[13]. C.K. Rao, "A comprehensive review of smart energy management," ScienceDirect (2025). Available: https://www.sciencedirect.com/science/article/pii/S2666519025000639

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25nov108

[14]. N. H. Alombah et al., "Advanced IoT-based monitoring system for real-time PV monitoring," (2025). Available: https://www.sciencedirect.com/science/article/pii/S2468227625002327
[15]. [O.H. Boucif et al., "Artificial Intelligence of Things for Solar Energy Monitoring," Applied Sciences (2025). Available: https://www.mdpi.com/2076-3417/15/11/6019
Arduino project hub resources: https://create.arduino.cc/projecthub
[16]. "IoT Based Solar Power Monitoring System with ESP32," How2Electronics tutorial. Available: https://how2electronics.com/iot-based-solar-power-monitoring-system-with-esp32/
Arduino IoT examples: https://create.arduino.cc/projecthub
[17]. Arduino & ESP32 project pages (practical microcontroller choices) and IoT communication notes. Example: https://create.arduino.cc/projecthub and https://how2electronics.com/iot-based-solar-power-monitoring-system-with-esp32/
[18]. Industry and research on IoT/cloud analytics and predictive maintenance: Alombah et al. (2025) SciDirect; Ledmaoui et al., "Review of Recent Advances in Predictive Maintenance," PMC (2025). Available: https://www.sciencedirect.com/science/article/pii/S2468227625002327
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC11722890/
[19]. National Renewable Energy Laboratory (NREL), "Fall 2024 Solar Industry Update," NREL, Oct. 30, 2024. Available: https://docs.nrel.gov/docs/fy25osti/92257.pdf. (NREL)
[20]. A. Redekar et al., "Functionality Analysis of Electric Actuators in Renewable Applications," *International Journal / PMC,* 2022. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9185451/. (PMC)
[21]. Z. Li et al., "Photovoltaic power generation enhancement performance with a LDR-based dual-axis solar tracking system," *Clean Technologies and Recycling,* 2025. Available: https://www.aimspress.com/article/doi/10.3934/ctr.2025007. (AIMS Press)
[22]. Espressif Systems, "ESP32 Series Datasheet," Espressif, 2025 (latest datasheet). Available: https://www.espressif.com/sites/default/files/documentation/esp32_datasheet_en.pdf. (Espressif)
[23]. M. Ross, "Solar Energy Monitoring with Raspberry Pi and Node-Red," blog/project, 2022–2024. Available: https://mitchross09.medium.com/solar-energy-monitoring-with-raspberry-pi-and-node-red-ed59e287cdd4. (Medium)
[24]. EMQ, "What Is The MQTT Protocol?" EMQ blog, 2023. Available: https://www.emqx.com/en/blog/what-is-the-mqtt-protocol. (www.emqx.com)
[25]. LoRa Alliance, "LoRaWAN Regional Parameters (v1.0.3)," LoRa Alliance, 2018. Available: https://lora-alliance.org/wp-content/uploads/2020/11/lorawan_regional_parameters_v1.0.3reva_0.pdf. (LoRa Alliance®)
[26]. I. Reda and A. Andreas, "Solar Position Algorithm for Solar Radiation Applications," NREL Technical Report, 2004. Available: https://midcdmz.nrel.gov/spa/. (midcdmz.nrel.gov)
[27]. A. Musa et al., "A Review of Time-Based Solar Photovoltaic Tracking Systems," *MDPI*, 2023. Available: https://www.mdpi.com/2078-2489/14/4/211. (MDPI)
[28]. Food and Agriculture Organization (FAO), "Dryer construction for solar-dried fruit and vegetables production," FAO resources, 1996–2020. Available: https://www.fao.org/family-farming/detail/en/c/1620466/. (FAOHome)
[29]. ColdHubs Limited, "ColdHubs Annual Impact Report (2023/2024)," ColdHubs, 2024. Available: https://coldhubs.com/2024/01/30/2024-1-30-coldhubs-annual-impact-report/. (ColdHubs)
[30]. K. Wang et al., "Real-time monitoring and energy consumption management for cold chains using IoT," *Energy Informatics,* 2025. Available: https://energyinformatics.springeropen.com/articles/10.1186/s42162-025-00493-w. (SpringerOpen)
[31]. "US solar tracker dominance offers learnings for other markets," *Reuters*, Aug. 8, 2024. Available: https://www.reuters.com/business/energy/us-solar-tracker-dominance-offers-learnings-other-markets-2024-08-08/. (Reuters)
[32]. IoT-Analytics, "LPWAN market insights," IoT-Analytics, 2024. Available: https://iot-analytics.com/lpwan-market/. (IoT Analytics)
[33]. HiveMQ, "2022 survey shows MQTT adoption is high for Industry 4.0," HiveMQ blog, Oct. 2022. Available: https://www.hivemq.com/blog/2022-survey-shows-mqtt-adoption-is-high-for-industry/. (hivemq.com)
[34]. F. Adelantado et al., "Understanding the Limits of LoRaWAN," *arXiv/IEEE* (analysis), 2016–2020. Available: https://arxiv.org/pdf/1607.08011.pdf. (arXiv)
[35]. H. J. J. Ochoa et al., "Comparative Analysis — MQTT power consumption study," *PMC*, 2023. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10224120/. (PMC)
[36]. S. A. Pelaez, C. Deline, P. Greenberg, J. Stein, R. K. Kostuk, "Model and Validation of Single-Axis Tracking with Bifacial Photovoltaics," National Renewable Energy Laboratory (NREL) preprint, 2018. Available: https://docs.nrel.gov/docs/fy19osti/72039.pdf. (NREL)
[37]. Lawrence Berkeley National Laboratory (LBNL), "Utility-Scale Solar, 2024 Edition," Oct. 2024. Available: https://eta-publications.lbl.gov/sites/default/files/2024-10/utility_scale_solar_2024_edition_slides.pdf. (LBL ETA Publications)
[38]. NREL, "Utility-Scale PV | Electricity | 2024 ATB," NREL ATB web page (2024). Available: https://atb.nrel.gov/electricity/2024/utility-scale_pv. (ATB)
[39]. "Model and Validation of Single-Axis Tracking With Bifacial PV," NREL research-hub entry. Available: https://research-hub.nrel.gov/en/publications/model-and-validation-of-single-axis-tracking-with-bifacial-photov. (National Renewable Energy Laboratory)

[40]. "AI-Powered Predictive Maintenance for Solar Energy – Case Study (75 MW)," International Journal of Financial Management Research (IJFMR) case paper, 2024. Available: https://www.ijfmr.com/papers/2024/6/30731.pdf. (IJFMR)

[41]. "AI Predictive Maintenance for Solar Systems," EasySolar (industry case/summary), 2025. Available: https://easysolar.app/cs/ai-predictive-maintenance-for-solar-systems/. (EasySolar)

[42]. J. V. Santos de Araújo et al., "Solar Tracking Control Algorithm Based on Artificial Intelligence," *Sensors* (MDPI), 2024. Available: https://www.mdpi.com/1424-8220/24/12/3890. (MDPI)

[43]. M. Phiri et al., "Deep learning techniques for solar tracking systems — systematic review," *Renewable Energy / ScienceDirect* (2023). Available: https://www.sciencedirect.com/science/article/abs/pii/S0038092X23004280. (ScienceDirect)

[44]. J. A. Carballo et al., "Machine Learning for Solar Trackers," AIP Conference Proceedings / research paper, 2019. Available (PDF): https://pubs.aip.org/aip/acp/article-pdf/doi/10.1063/1.5117524/14189442/030012_1_online.pdf. (AIP Publishing)

[45]. K. Kumba, "Solar tracking systems: Advancements, challenges, and future trends," *Renewable and Sustainable Energy Reviews*, 2024. Available: https://www.sciencedirect.com/science/article/pii/S2352484724006164. (ScienceDirect)

[46]. "US solar tracker dominance offers learnings for other markets," *Reuters*, Aug. 8, 2024. Available: https://www.reuters.com/business/energy/us-solar-tracker-dominance-offers-learnings-other-markets-2024-08-08/. (Reuters)

[47]. Forescout Research – Vedere Labs, "The security risks of internet-exposed solar power systems / SUN:DOWN findings," blog/report summary, 2025. Available: https://www.forescout.com/blog/the-security-risks-of-internet-exposed-solar-power-systems/. (Forescout)

[48]. "35,000 Solar Power Systems Exposed to Internet," *SecurityWeek*, Jun. 4, 2025. Available: https://www.securityweek.com/35000-solar-power-systems-exposed-to-internet/. (SecurityWeek)

[49]. DERSec, "Public history of solar energy cyberattacks and vulnerability summary (SUN:DOWN & ecosystem analysis)," report PDF, 2025. Available: https://dersec.io/reports/DERSec-Solar-Vulnerability-Summary-v2.0-Final.pdf. (dersec.io)

[50]. A. Rekeraho et al., "Cybersecurity Threat Modeling for IoT-Integrated Smart Solar Energy Systems," *Sustainability* (MDPI), 2025. Available: https://www.mdpi.com/2071-1050/17/6/2386. (MDPI)

[51]. "Guarding the grid: Cybersecurity in solar and renewable," *PV-Magazine USA*, Jun. 27, 2025. Available: https://pv-magazine-usa.com/2025/06/27/guarding-the-grid-cybersecurity-in-solar-and-renewable-energy/. (pv magazine USA)

[52]. "Artificial Intelligence of Things for Solar Energy Monitoring and Control," ResearchGate review, May 21, 2025. Available: https://www.researchgate.net/publication/392181084_Artificial_Intelligence_of_Things_for_Solar_Energy_Monitoring_and_Control

[53]. U. Mamodiya et al., "Numerical modeling and neural network optimization for …" *Scientific Reports / Nature* (2025). Available: https://www.nature.com/articles/s41598-025-06830-z

[54]. SolarPower Europe, "Global Market Outlook for Solar Power 2025–2029," May 6, 2025. Available: https://www.solarpowereurope.org/insights/outlooks/global-market-outlook-for-solar-power-2025-2029/detail

[55]. "Solar Tracker Market | Future Outlook, Trends, and Expansion," Global Market Insights (GMI), 2024–2025 market report summary. Available: https://www.gminsights.com/industry-analysis/solar-tracker-market-report

[56]. Y. Ledmaoui et al., "Review of Recent Advances in Predictive Maintenance and Cybersecurity for Solar Plants," *Sensors* (MDPI), 2025. Available: https://www.mdpi.com/1424-8220/25/1/206