Published by :
https://www.ijert.org/
An International Peer-Reviewed Journal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 05, IIRA 5.0 (2026)

A Review Paper on Solar Tracking System

Prachi Agarwal[1],Kanchan Rani[2],Rakshak Chauhan [3], Sandeep kumar[4], Prashant Singh[5], Sarthak Rastogi [6]

[1, 2] Assistant Professor, Computer Science and Engineering Department, MIT, Moradabad, India

reachtoprachi@gmail.com

kanchansinghcs@gmail.com

[3,4,5,6] Computer Science and Engineering Department, MIT, Moradabad, India

chauhanrakshak803@gmail.com

ksandeep6983@gmail.com

prashants8076@gmail.com

sarthakrastogi03@gmail.com

ABSTRACT

Solar energy is one of the most promising renewable energy sources, but the efficiency of solar photovoltaic (PV) systems is often limited by the fixed positioning of solar panels, which cannot continuously align with the sun's changing position. Solar tracking systems have been developed to address this challenge by dynamically adjusting the orientation of solar panels to maintain optimal alignment with the sun throughout the day and across seasons. This paper provides a comprehensive overview of solar tracking technology, including its fundamental principles, types, key components, and control mechanisms. Two primary types of trackers—single-axis and dual-axis—are examined in detail, highlighting their operational differences, energy yield improvements, and cost implications. Single-axis trackers, which rotate panels along one axis, offer moderate efficiency gains with simpler design and lower maintenance, while dual-axis trackers provide maximum energy capture by allowing movement along two axes but involve higher complexity and cost. The integration of sensors, microcontrollers, and advanced algorithms enables precise and automated tracking, improving system responsiveness and reliability. Performance analyses from various studies demonstrate that solar tracking systems can increase energy production by 15% to over 50%, depending on the tracker type and geographic location. Despite their advantages, challenges such as higher initial investment, mechanical wear, and environmental susceptibility remain. The paper also discusses emerging trends, including the incorporation of artificial intelligence, Internet of Things (IoT) connectivity, and predictive maintenance, which promise to enhance the efficiency, scalability, and cost-effectiveness of solar trackers. In conclusion, solar tracking systems represent a vital technological advancement that can significantly boost the performance of solar PV installations, contributing to the global transition toward sustainable and clean energy solutions.

KEYWORDS

Photovoltaic , solar Tracker , Renewable Energy Sources (RES), STS (Solar Tracker System)

1. INTRODUCTION

The global shift toward renewable energy sources has intensified the focus on solar photovoltaic (PV) technology as a sustainable solution to meet rising energy demands and mitigate climate change. However, the efficiency of conventional static solar panels remains constrained by their fixed orientation, which limits their ability to capture sunlight optimally as the sun's position shifts throughout the day and across seasons. Solar tracking systems address this limitation by dynamically adjusting the angle of solar panels to maintain near-perpendicular alignment with incoming sunlight, thereby maximizing energy absorption and power generation.

Solar trackers are broadly categorized into single-axis and dual-axis systems, each offering distinct advantages in terms of energy yield, cost, and complexity. Single-axis trackers rotate panels along one axis—typically east-west—to follow the sun's daily path, while dual-axis systems incorporate additional vertical movement to account for seasonal variations in solar elevation. These systems leverage a combination of sensors, actuators, microcontrollers, and software algorithms to achieve precise orientation control, enabling significant improvements in energy output compared to fixed installations.

The growing adoption of solar tracking technology reflects its potential to enhance the economic viability of solar energy projects. Studies indicate that single-axis trackers can boost energy production by 15–25%, while dual-axis systems may achieve gains of up to 45–50%, depending on geographic location and climatic conditions. Despite these benefits, challenges such as higher upfront costs, mechanical complexity, and maintenance requirements necessitate careful consideration during system design and deployment.

This paper explores the principles, components, and performance characteristics of solar tracking systems, emphasizing their role in advancing renewable energy infrastructure. By examining current innovations, including AI-driven predictive tracking and IoT-enabled monitoring, the discussion highlights how ongoing technological advancements are addressing existing limitations and expanding the applicability of solar trackers in diverse environments. The analysis underscores the critical importance of solar tracking systems in optimizing energy harvest, reducing carbon footprints, and accelerating the global transition to clean energy solutions.

2. PRINCIPLE OF SOLAR TRACKING

Solar tracking systems are engineered to maximize the efficiency of photovoltaic (PV) panels by continuously adjusting their orientation to follow the sun's movement across the sky. The fundamental principle is to maintain the solar panel surface as perpendicular as possible to the sun's rays throughout the day, thereby optimizing sunlight exposure and energy generation

2.1 Core Working Principle:

By tracking the sun's position in real time, solar trackers minimize the angle of incidence—the angle between incoming sunlight and the panel surface. A smaller angle of incidence allows more solar radiation to be absorbed, significantly increasing power output compared to fixed panels. Even a deviation of 25° from the optimal angle can reduce energy output by about 10% .

2.2 Types of Solar Tracking :

2.2.1 Active Tracking:

Uses motors, sensors, and controllers to physically move the panels in response to the sun's position. Active trackers rely on continuous feedback from sensors or algorithms to adjust orientation.

2.2.2 Passive Tracking:

Utilizes temperature or pressure changes to move panels, typically with less precision and slower response than active systems.

2.3 Tracking Algorithms and Control Methods:

Solar tracking algorithms are central to system performance. They calculate the sun's position using parameters such as time, date, latitude, and longitude, and send commands to adjust the panel's orientation.

2.3.1 Light Sensor (Photoelectric) Control:

Sensors detect differences in sunlight intensity on different parts of the tracker. When an imbalance is detected, the system activates motors to reorient the panel until the sensors are balanced, ensuring perpendicular alignment with the sun.

2.3.2 Time/Astronomical Control:

The system uses pre-programmed astronomical data (based on local latitude, longitude, and time) to predict the sun's position and adjust the panels accordingly. GPS modules can enhance accuracy by providing real-time location and time data.

2.3.3 Hybrid Control:

Combines light sensor and time-based methods to improve tracking precision. For example, time control may provide coarse alignment, while light sensors fine-tune the orientation. Some advanced systems switch between modes depending on weather conditions or use AI and machine learning to further optimize performance.

2.3.4 System Components

Key components of a solar tracking system include:

Tracker Mount: Holds and supports the solar panel.

Sensors: Detect sunlight or provide positional data.

Motors/Actuators: Move the panels based on control signals.

Controller/Algorithm: Processes sensor input or time data to determine optimal orientation.

2.3.5 Efficiency and Benefits

Solar tracking systems can increase energy yield by 10–20% for single-axis trackers and up to 25% or more for dual-axis systems, depending on geographic and climatic conditions. By maintaining optimal orientation, trackers reduce reflection losses and improve the overall return on investment for solar installations.

In summary, the principle of solar tracking is to maximize solar energy absorption by dynamically aligning PV panels with the sun's position, using a combination of mechanical movement, sensor feedback, and advanced algorithms to achieve high precision and efficiency.

3. TYPES OF SOLAR TRACKING SYSTEMS

3.1 Single-Axis Solar Trackers:

Single-axis trackers rotate solar panels around one fixed axis, typically allowing movement from east to west to follow the sun's daily path. These are further subdivided into:

3.1.1 Horizontal Single-Axis Tracker (HSAT):

Rotates panels on a horizontal axis parallel to the ground, ideal for flat, sunny areas.

3.1.2 Horizontal Tilted Single-Axis Tracker (HTSAT):

Similar to HSAT but installed at a tilt for improved performance at certain latitudes.

3.1.3 Vertical Single-Axis Tracker (VSAT):

Rotates on a vertical axis, often used in regions with significant seasonal sun angle changes or mountainous terrain.

3.1.4 Vertical-Tilted Single-Axis Tracker (VTSAT):

Combines vertical tilt with rotation, offering higher energy harvest but requiring more structural support and materials.

Single-axis trackers are simpler and more cost-effective than dual-axis systems and can increase energy yield by 15–25% compared to fixed panels.

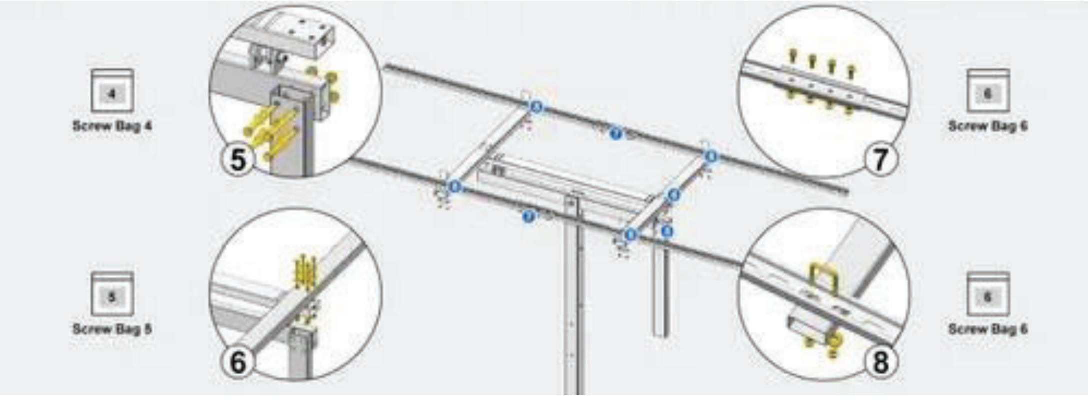


Figure 1: Single Axis Tracker

3.2. Dual-Axis Solar Trackers

Dual-axis trackers allow solar panels to move along both horizontal and vertical axes. This enables them to follow the sun's elevation (up-down) and azimuth (east-west) angles throughout the day and year. The two common types are:

3.2.1 Tip-Tilt Dual-Axis Trackers:

Panels tilt in both east-west and up-down directions.

3.2. 2 Azimuth-Altitude Dual-Axis Trackers:

Panels rotate in azimuth (horizontal plane) and adjust altitude (vertical plane) for precise sun tracking. Dual-axis trackers maximize solar energy capture, making them suitable for commercial-scale installations and locations with significant seasonal variation in sunlight. They can boost energy production by up to 45–50% over fixed systems but are more complex and expensive.

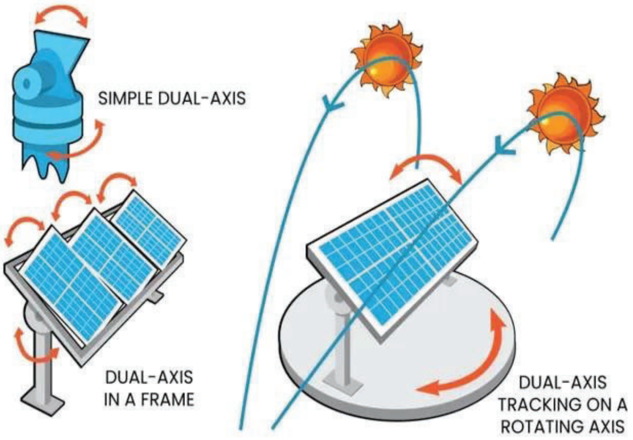


Figure 2: Dual Axis Tracker

3.3. Active Tracking Devices

Active trackers use motors and sensors to detect the sun's position and adjust the panel orientation accordingly. They are powered by external energy sources and can be further divided into:

3.3.1 Open Loop Trackers:

Operate based on pre-programmed algorithms or time schedules without real-time feedback.

3.3.2 Timed Trackers:

Adjust panels at set intervals based on predicted sun position.

3.3.3 Altitude/Azimuth Trackers:

Use calculated sun positions for precise movement.

3.3.4 Closed Loop Trackers:

Utilize real-time sensor feedback (such as light sensors) to continuously optimize the panel's angle. Active systems are common in large and complex solar installations due to their higher precision and adaptability.

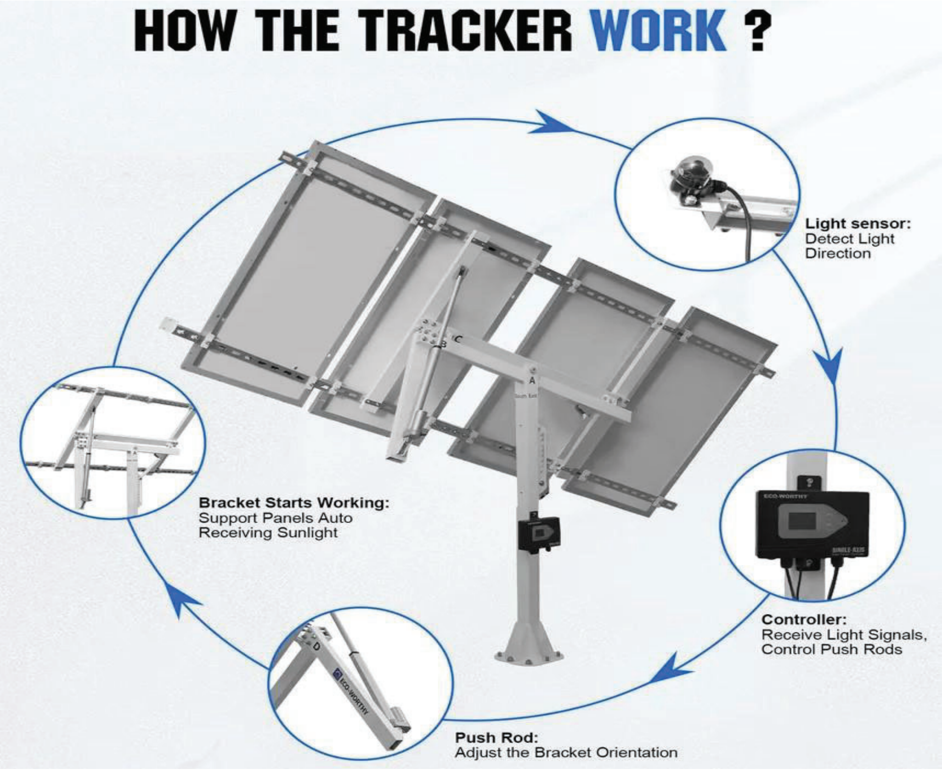
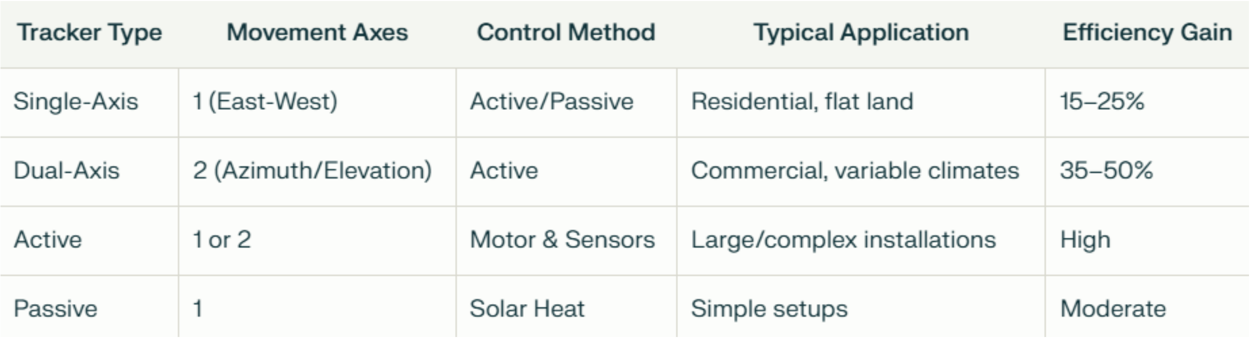


Figure 3: Tracker Work

3.4. Passive Tracking Devices

Passive trackers do not require external power. Instead, they rely on the sun’s heat to trigger movement. Typically, a gas or fluid expands when heated, causing a mechanical shift that reorients the panel toward the sun. As the sun moves, the process repeats, tracking the sun’s path without electrical input. Passive systems are simpler but generally less precise than active trackers.

Summary Table



Tracker Type	Movement Axes	Control Method	Typical Application	Efficiency Gain
Single-Axis	1 (East-West)	Active/Passive	Residential, flat land	15–25%
Dual-Axis	2 (Azimuth/Elevation)	Active	Commercial, variable climates	35–50%
Active	1 or 2	Motor & Sensors	Large/complex installations	High
Passive	1	Solar Heat	Simple setups	Moderate

Solar tracking systems, whether single-axis, dual-axis, active, or passive, play a crucial role in maximizing the efficiency and output of solar PV installations by ensuring optimal panel orientation throughout the day and year.

4. KEY COMPONENTS AND CONTROL STRATEGIES

A solar tracking system relies on a combination of mechanical, electrical, and computational components to ensure solar panels maintain optimal alignment with the sun, thereby maximizing energy output. Below are the essential components and the control strategies that govern their operation:

4.1 Key Components :

4.1.1 Solar Panels:

The core element that converts sunlight into electricity.

4.1.2 Tracker Mount/Frame:

A robust structure that supports the solar panel(s) and enables their movement along one or more axes. Materials like steel or aluminum are commonly used to withstand environmental stresses.

4.1.3 Sensors:

Devices such as light-dependent resistors (LDRs), photodiodes, or small auxiliary solar cells detect the sun’s position by measuring light intensity or voltage differences. These sensors provide real-time feedback for precise alignment.

4.1.4 Microcontroller/Control Unit:

This is the system's "brain," processing sensor data and executing the tracking algorithm. It generates control signals for the actuators or motors based on sun position calculations or sensor feedback.

4.1.5 Motors/Actuators:

Stepper motors, servo motors, or hydraulic actuators physically move the tracker mount to adjust the solar panel's orientation. The choice depends on the system's size and complexity.

4.1.6 Driver Circuit:

Interfaces between the microcontroller and motors, ensuring accurate and safe movement by controlling power and direction.

4.1.7 Power Supply/Battery:

Provides energy to operate the control electronics and actuators, often supplemented by the solar panel itself.

4.1.8 Signal Conditioning and Processing Units:

These circuits refine sensor signals to ensure accurate input for the controller.

4.1.9 Additional Elements:

In advanced systems, programmable logic controllers (PLCs), encoders, and communication modules may be included for enhanced automation and monitoring.

4.2 Control Strategies

4.2.1 Sensor-Based (Closed-Loop) Control:

Sensors compare sunlight intensity on different parts of the tracker. If an imbalance is detected, the microcontroller commands the motor to adjust the panel until both sensors receive equal light, ensuring perpendicular alignment with the sun. This real-time feedback loop allows the system to adapt to changing sunlight conditions throughout the day.

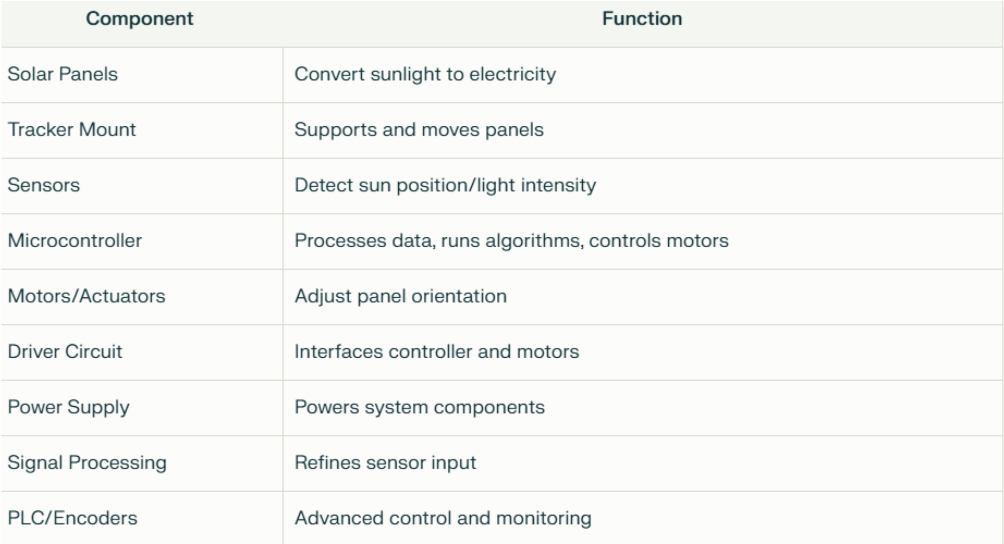
4.2.2 Algorithm-Based (Open-Loop) Control:

Instead of relying on real-time sensor feedback, these systems use pre-programmed astronomical algorithms that calculate the sun's position based on the date, time, and geographic coordinates. The microcontroller then moves the panels according to these calculations, often using GPS data for increased accuracy. This method reduces dependency on sensors and can be more reliable in cloudy or variable weather.

4.2.3 Hybrid Control:

Some advanced trackers combine both sensor-based and algorithm-based approaches. The algorithm provides a baseline orientation, while sensors fine-tune the alignment, or the system switches between methods depending on environmental conditions for maximum efficiency and reliability.

4. Summary Table



Component	Function
Solar Panels	Convert sunlight to electricity
Tracker Mount	Supports and moves panels
Sensors	Detect sun position/light intensity
Microcontroller	Processes data, runs algorithms, controls motors
Motors/Actuators	Adjust panel orientation
Driver Circuit	Interfaces controller and motors
Power Supply	Powers system components
Signal Processing	Refines sensor input
PLC/Encoders	Advanced control and monitoring

5. PERFORMANCE ANALYSIS

Performance analysis of solar tracking systems focuses on evaluating how effectively these systems enhance the energy output of photovoltaic (PV) panels compared to fixed installations. Multiple studies and practical implementations consistently demonstrate that solar trackers, particularly single-axis and dual-axis designs, significantly improve the efficiency and energy yield of solar power systems.

5.1 Energy Output and Efficiency Gains :

5.1.1 Single-Axis Trackers:

Single-axis solar tracking systems, which follow the sun’s movement either horizontally or vertically, typically increase energy production by 15–25% compared to fixed panels. Performance evaluations show that these systems maintain a more optimal angle of incidence throughout the day, resulting in higher voltage and current outputs. For instance, a study found that a microcontroller-based single-axis tracker achieved a 47.5% increase in power output over a fixed panel under similar conditions.

5.1.2 Dual-Axis Trackers:

Dual-axis trackers, capable of adjusting both azimuth and elevation, further maximize sunlight capture and can boost energy yield by 35–50% over static systems. These trackers are particularly effective in locations with high variability in the sun’s position throughout the year. Comparative analyses reveal that dual-axis systems consistently outperform single-axis trackers, especially in terms of total daily and seasonal energy collection.

5.2 System Optimization and Monitoring

5.2.1 Sensor Integration:

The integration of sensors (such as LDRs) and microcontrollers enables real-time tracking and dynamic adjustment, ensuring panels remain perpendicular to sunlight. Performance monitoring using voltage, current, and temperature sensors allows for remote data collection and system optimization, often via IoT platforms.

5.2.3 Environmental Factors:

The efficiency of solar trackers is influenced by environmental conditions such as solar irradiation, temperature, and local weather patterns. Performance tends to be highest in regions with clear skies and high solar i solation, while cloudy or variable weather can reduce the relative advantage of tracking systems.

5.3 Cost and Feasibility Considerations

5.3.1 Economic Analysis:

While solar tracking systems significantly increase energy output, they also involve higher initial costs and maintenance compared to fixed systems. Dual-axis trackers, in particular, may not be economically feasible for all installations due to their complexity and expense, despite their superior performance. Single-axis trackers offer a balanced approach, delivering substantial gains at a more accessible cost.

5.4 Sustainability and Practical Impact

5.4.1 Environmental Benefits:

Optimized solar tracking systems not only improve energy efficiency but also contribute to sustainability by reducing reliance on fossil fuels and minimizing waste and pollution associated with energy generation.

6. FUTURE PROSPECTS

The evolution of solar tracking systems is poised to accelerate with advancements in technology, materials science, and digital innovation. Below are key areas expected to shape the future of solar tracking:

6.1. Integration with Artificial Intelligence (AI) and Machine Learning

6.1.1 Predictive Tracking:

AI algorithms will analyze historical weather data, cloud patterns, and real-time sky imagery to predict sun paths and optimize panel orientation proactively, even under variable weather conditions.

6.1.2 Fault Detection:

Machine learning models will enable self-diagnosing systems capable of identifying mechanical wear, electrical faults, or shading issues, reducing downtime and maintenance costs.

6.2. Internet of Things (IoT) and Smart Grid Compatibility

6.2.1 Remote Monitoring:

IOT-enabled trackers will transmit performance metrics (e.g., energy output, panel tilt) to cloud platforms for real-time analysis and remote adjustments.

6.2.2 Grid Synchronization:

Trackers will integrate with smart grids to balance energy supply and demand dynamically, feeding excess power during peak production and reducing strain during low generation.

6.3. Advanced Materials and Lightweight Designs

6.3.1 Carbon Fiber Frames:

Lightweight, corrosion-resistant materials will reduce structural loads and extend tracker lifespans, even in harsh environments.

6.3.2 Self-Cleaning Coatings:

Hydrophobic or photo catalytic coatings on panels will minimize dust accumulation, maintaining efficiency without manual intervention

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6.4. Energy Storage Integration

6.4.1 Battery Synchronization:

Trackers will work in tandem with advanced battery systems to store excess energy during peak sunlight hours, ensuring stable power supply during nighttime or cloudy periods.

6.4.2 Thermal Storage:

Excess heat from concentrated solar systems (CSP) paired with trackers could be stored in molten salt or phase-change materials for later use.

6.5. Cost Reduction and Scalability

6.5.1 Modular Designs:

Plug-and-play tracker kits will simplify installation and reduce labour costs, making the technology accessible to small-scale residential users.

6.5.2 3D-Printed Components:

Additive manufacturing will lower production costs for custom parts, such as gears and sensor housings.

6.6. Policy and Market Trends

6.6.1 Government Incentives:

Subsidies for AI-driven or IoT-enabled trackers will accelerate adoption in emerging markets.

6.6.2 Carbon Credit Systems:

Solar tracking projects will increasingly leverage carbon trading platforms to offset installation costs.

7. RESULT

Solar tracking systems significantly enhance energy output compared to fixed solar panels, with single-axis trackers achieving 15–25% higher efficiency and dual-axis systems delivering 35–50% increased energy production, driven by their ability to maintain optimal alignment with the sun’s path. While single-axis trackers offer cost-effective payback periods of 3–5 years in high-insolation regions, dual-axis systems, despite superior efficiency, face longer payback periods (5–8 years) due to higher upfront costs and maintenance needs. Environmental benefits include reduced CO_2 emissions (20–30% per kWh) and improved land-use efficiency, particularly with dual-axis trackers maximizing output in space-constrained areas. Technological advancements such as AI-driven predictive tracking, IoT-enabled remote monitoring, and lightweight materials enhance reliability and adaptability, though challenges like mechanical wear and weather sensitivity persist. Future innovations, including space-based solar farms and agrivoltaic integration, promise further efficiency gains, positioning solar trackers as pivotal tools in advancing global renewable energy adoption.

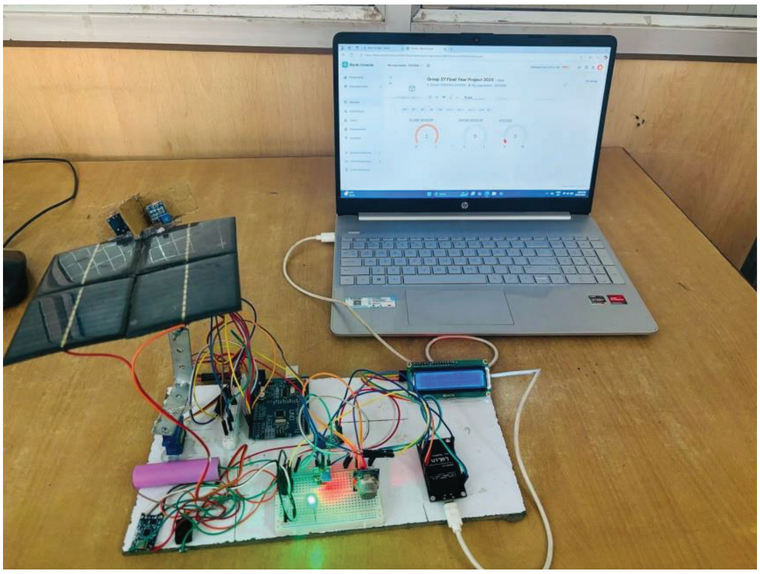
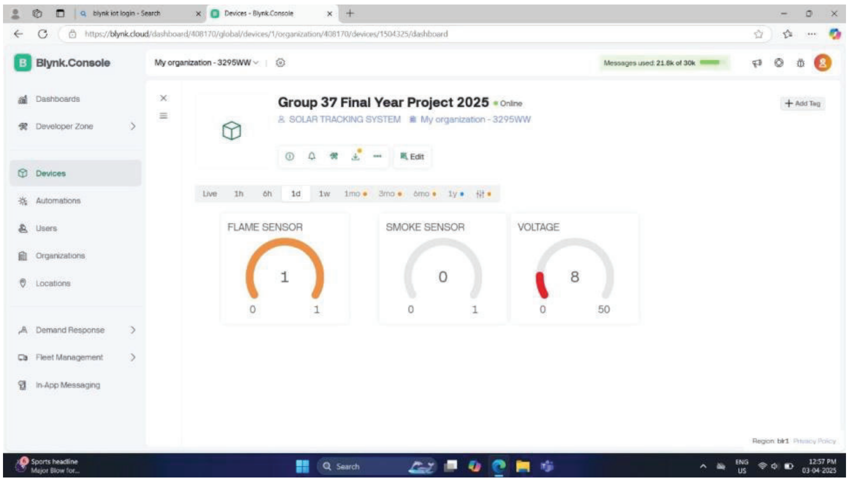


Figure 4 Model



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SOLAR TRACKING SYSTEM   My organization - 3295WW

FLAME SENSOR 1 (0–1)

SMOKE SENSOR 0 (0–1)

VOLTAGE 8 (0–50)

Figure 5 Dashborad

8. CONCLUSION

Solar tracking systems represent a transformative advancement in solar energy technology, addressing the inherent limitations of static photovoltaic installations by dynamically optimizing panel orientation to maximize sunlight capture. Through single-axis and dual-axis configurations, these systems achieve significant efficiency gains—ranging from 15% to over 50%—depending on design complexity and environmental factors. While dual-axis trackers deliver superior energy output, single-axis systems offer a practical balance of cost and performance, making them ideal for widespread residential and commercial adoption. Despite challenges such as mechanical wear and higher initial costs, advancements in AI-driven predictive tracking, IoT integration, and durable materials are mitigating these barriers, enhancing reliability and scalability. The environmental benefits, including reduced carbon footprints and improved land-use efficiency, further underscore their role in global sustainability efforts. As innovations in hybrid energy systems, agrivoltaics, and space-based solar tracking emerge, these technologies are poised to play a pivotal role in accelerating the transition to renewable energy, ensuring cleaner, more efficient power generation for future generations.

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Authors

Prachi Agarwal is an Assistant Professor in the Department of Computer Science & Engineering , Moradabad Institute of Technology, Moradabad .She completed her MTech degree in Computer Science from IFTM University in 2013. She pursued her BTech degree from GBTU Lucknow. She has published more than 19 research papers in various international journals and conferences. She has more than 11years teaching experience. Her research interests include Machine Learning, web development and image processing.

Kanchan Rani is an Assistant Professor in the Department of Computer Science & engineering, Moradabad Institute of Technology, Moradabad. She completed her MTech degree in Computer Science from Banasthali Vidyapith Jaipur in 2011. She pursued her BTech degree from AKTU Lucknow. She has published more than 18 research papers in various international journals and conferences. She has more than 16 years teaching experience. Her research interests include Artificial Intelligence, Machine Learning, software engineering and soft computing techniques.

Rakshak Chauhan is pursuing (doing) the BTech in Computer Science & Engineering from Moradabad Institute of Technology, Moradabad. His areas of interest include full stack web development.

Sandeep kumar is pursuing (doing) the BTech in Computer Science & Engineering from Moradabad Institute of Technology, Moradabad. His areas of interest include full stack web development.

Prashant Singh is pursuing (doing) the B.Tech in Computer Science and Engineering from Moradabad Institute of Technology ,Moradabad. Her areas of interest include Web development and Database Management System.

Sarthak Rastogi is pursuing (doing) the BTech in Computer Science & Engineering from Moradabad Institute of Technology, Moradabad. Her areas of interest include full stack developer.