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Article

IoT Enabled Smart Solar Tracking Systems with Artificial Intelligence Emerging Trends, Challenges, and Future Directions

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Abstract: The development of intelligent solar energy management systems has increased due to the growing demand for renewable energy and the requirement for improved photovoltaic (PV) efficiency. Dust buildup, shifting sunlight angles, and ineffective monitoring systems cause conventional solar panels in fixed positions to extract minimum energy. This work suggests an IoT, Raspberry Pi and AI-based smart solar tracking with monitoring system, as a solution to these problems. To optimize solar power production, the suggested system combines dual-axis sun tracking, wireless monitor-ing, real-time sensing, and automated cleaning. Sensors are used to continually monitor electrical and environmental factors such panel voltage, current, power, temperature, and light intensity. The main controller for data collection, processing, and actuator control is a Raspberry Pi 3B+. In order to maximize sunshine exposure, the system dynamically modifies panel orientation using twin DC motors based on inputs from LDR and BH1750 sensors. Remote monitoring via a web dashboard is proposed by IoT connectivity. According to experimental findings, tracking mode produced an average output voltage of 12.24 V as opposed to 11.35 V in stationary mode, a 7.82% improvement is observed. Additionally, the suggested approach minimized dust-related efficiency losses through automated cleaning and average power generation increased by about 18.6%. Smart maintenance recommendations, anomaly detection, and performance prediction are further presented by AI-based analytics. The findings show that Intelli Solar offers next-generation smart photovoltaic energy systems an effective, affordable, and scalable solution.
Keywords: Photovoltaic cell, Internet of Things (IoT), Dual axis tracking, Artificial Intelligence, Raspberry Pi.

1. Introduction

Energy is a fundamental requirement for the economic and technological development of any nation. With the rapid growth in population, industrialization, and urbanization, the global demand for energy has increased significantly over the past few decades [1]. Traditionally, this demand has been met using conventional energy sources such as coal, petroleum, and natural gas [2]. However, these resources are finite in nature and contribute heavily to environmental degradation through greenhouse gas emissions, air pollution, and global warming [3]. This has led to an urgent need for cleaner, sustainable, and renewable energy alternatives. Solar energy systems have gained widespread adoption in recent years due to their numerous advantages [4]. They are environmentally friendly, as they produce no harmful emissions during operation. Despite these advantages, solar energy systems are not without limitations [5]. The efficiency of solar panels is influenced by several environmental and operational factors [6]. Dust accumulation on panel surfaces can block sunlight and reduce energy output [7]. Temperature variations, especially high temperatures, can decrease the efficiency of photovoltaic cells. Another significant challenge is the lack of intelligent monitoring and control in traditional solar systems [8]. Most conventional setups do not provide real-time data regarding system performance, making it difficult to detect faults or inefficiencies [9]. This can result in reduced energy output, increased maintenance costs, and potential system failures [10]. In order to overcome these challenges, there is a growing trend toward integrating advanced technologies such as the Internet of Things (IoT), Artificial

Intelligence (AI), and automation into solar energy systems. These technologies enable real-time monitoring, predictive analysis, and automated control, significantly improving system efficiency and reliability [11].

2. Background & Motivation

The rapid growth in global energy demand, combined with the environmental impact of fossil fuels, has led to a shift toward renewable energy sources [12]. Solar energy, being abundant and sustainable, has gained significant importance in recent years. The efficiency and performance of solar systems depend heavily on proper maintenance and optimal operation [13]. Practical observations indicate that factors such as dust accumulation, overheating, and lack of monitoring significantly affect system performance. A remote monitoring system prototype created by J.A. Torres Cepeda et al. [14] for environmental conservation and protection in the Colombian Amazon Rainforest is described in this IEEE Latin America Transactions article. The system is customized for particular local, climatic, and geographical conditions. In order to provide precise synchronization and reliable control, K. Dutt et al., [15] suggests a Digital Twin (DT)-based real-time stability assessment framework for grid-connected PV systems using the RAAEFO (Root Average Absolute Error Fitness Optimization) algorithm and an AR-CSOGI (Adaptive Resonance Current Second-Order Generalized Integrator) based UVI-CFESMC (Unified Voltage Injection–Cross Feedback Error Sliding Mode Controller) controller. This has motivated researchers and engineers to develop intelligent systems that can enhance solar energy utilization. The integration of IoT enables real-time monitoring and data collection, while AI techniques allow predictive analysis and smart decision-making. In order to increase fault diagnosis accuracy and PV system reliability, Yang [16] suggests an LSTM-based neural network for photovoltaic defect detection under various irradiance situations. Another significant area of research is solar tracking technology. Traditional fixed solar panels are unable to maintain optimal alignment with the sun throughout the day, leading to reduced energy generation. To address this issue, researchers have developed single-axis and dual-axis tracking systems that adjust the orientation of solar panels based on the sun's position. Murthy et al., [17] describes an automated, Internet of Things-enabled method to maximize solar energy harvesting by utilizing Arduino, servo motors, and light-dependent resistors (LDRs) to adjust panels along horizontal and vertical axes. An Arduino UNO-based dual-axis solar tracking system with LDR sensors and servo motors for ideal solar panel alignment is used by Shimul et al., [18]. By integrating the ESP8266 with the Thing Speak IoT platform, the system outperformed fixed-axis solar panels in terms of efficiency by 21.83%. These systems have been proven to increase energy output significantly, making them an important advancement in solar technology. In recent years, the integration of the Internet of Things (IoT) into solar energy systems has gained considerable attention. In order to maximize solar radiation absorption, Monfared et al., [19] suggested for optimization solar panel tilt angles and adjustment timing. The findings indicate that dual-angle solar tracking with periodic adjustment outperforms fixed-angle installation. To decrease shading losses and increase PV output power, Xu et al., [20] proposes an enhanced backtracking algorithm for dual-axis solar tracking based on PSO. The suggested approach improves both overall solar efficiency and tracking precision. IoT-based monitoring systems enable real-time data collection and analysis of key parameters such as voltage, current, temperature, and light intensity. This allows for continuous performance evaluation, early fault detection, and remote system management, thereby improving operational efficiency and reliability. Furthermore, the application of Artificial Intelligence (AI) and machine learning techniques has opened new possibilities in solar energy optimization. AI-based systems can analyze large volumes of data to predict system performance, detect anomalies, and provide intelligent recommendations for maintenance and energy management. These capabilities significantly enhance the efficiency and adaptability of solar power systems under varying environmental conditions. Despite these advancements, existing systems still face several limitations, including high implementation costs, system complexity, and limited scalability in certain applications. Many systems also lack integration of multiple features such as tracking, cleaning, monitoring, and intelligent decision-making within a single platform. The motivation behind the work is to create a smart solar system that addresses the limitations of traditional systems. By combining automation, IoT and AI, the system aims to:

- Increase efficiency through solar tracking
- Maintain cleanliness through automated cleaning
- Enhance safety through temperature monitoring
- Provide real-time insights using a smart dashboard

The primary objective of this work is to develop an intelligent solar energy system that improves efficiency, reliability, and ease of maintenance.

The specific objectives are:

- To design and develop an AI-based smart solar monitoring system.
- To implement a dual-axis solar tracking mechanism for maximum sunlight exposure.
- To create an automated cleaning system using water pump and motor.
- To monitor key parameters such as voltage, light intensity, and temperature in real-time.
- To develop a web-based dashboard for live data visualization and control.
- To ensure safe operation by detecting overheating and abnormal conditions.
- To reduce manual intervention and operational costs.

3. Proposed System

The proposed system is designed to enhance the performance, efficiency, and reliability of conventional solar energy systems by integrating advanced technologies such as Artificial Intelligence (AI), Internet of Things (IoT), and automation. Traditional solar systems primarily focus on energy generation but often lack intelligent features for monitoring, optimization, and maintenance. Intelli Solar addresses these limitations by introducing a smart, automated, and data-driven approach to solar energy management. The system is capable of continuously monitoring environmental and electrical parameters, analyzing system performance, and making intelligent decisions to optimize energy output. At the core of the system lies a microcontroller or embedded platform, such as a Raspberry Pi, which acts as the central processing unit. This controller collects data from various sensors, including light sensors, voltage sensors, and temperature sensors. Based on the collected data, the system perform actions such as adjusting panel orientation, activating cleaning mechanisms, and generating alerts. The system is also equipped with IoT capabilities, allowing real-time data transmission to a web-based dashboard. This enables users to remotely monitor system performance, analyze trends, and control system operations. Additionally, AI-based analysis enhances decision-making by identifying inefficiencies and suggesting corrective actions.

A. Block Diagram of System

The Intelli Solar system is composed of several interconnected components that work together to achieve efficient energy generation and management is shown in fig 1. Although the system is represented using a block diagram, its functionality can be understood through the interaction of its major components. The solar panel serves as the primary energy source, converting sunlight into electrical energy. Sensors are integrated into the system to measure important parameters such as light intensity, voltage output, and temperature. These sensors provide continuous input data to the central controller. The microcontroller processes this data and determines appropriate actions. For example, it controls motors responsible for solar tracking, ensuring that the panel is always oriented toward maximum sunlight. It also manages relay modules to control devices such as water pumps used for cleaning. The system includes a communication module that enables data transmission to a web interface or cloud platform. This allows real-time monitoring and remote access. Additionally, a camera module is integrated for visual monitoring, providing an extra layer of system observation. All components are powered through a regulated power supply system, which may include batteries and charge controllers to ensure uninterrupted operation. Thus, the system operates as a coordinated network of sensing, processing, control, and communication units, forming a complete intelligent solar solution. The generated Solar Power can be calculated

$$P_{solar} = \eta A G \qquad (1)$$

where, P_{solar} Generated solar power (W), η is Solar panel efficiency, A is Area of solar panel (m^2), G is Solar irradiance (W/m^2). The best panel orientation, tracking is modified by reducing the light intensity error between LDR sensors. For Dual-Axis Solar Tracking Error function calculation

$$e(t)=\sum_{i=1}^{4} LDR_i \qquad (2)$$

The IoT energy monitoring equation is calculated by

$$E=\int_{0}^{T} P(t)dt \qquad (3)$$

where, E is the total energy generated, $P(t)$ is instantaneous power and T is operating duration. The Battery State of Charge (SOC) is calculated by

$$SOC=\frac{Q_{remaining}}{Q_{rated}}\times 100 \qquad (4)$$

The SOC is battery state of charge (%), $Q_{remaining}$ is remaining battery capacity and Q_{rated} is rated battery capacity. Motor Control Equation is written as

$$\omega=\frac{V-I_a R_a}{K\phi} \qquad (5)$$

where, ω is motor angular speed, V is applied voltage I_a is armature current, R_a is armature resistance and $K\phi$ is motor constant. The AI Loss Function can be calculated for minimizing prediction error in AI-based solar forecasting and tracking optimization.

$$Loss = \frac{1}{n}\sum_{i=1}^{n}(y_i-\hat{y}_i)^2 \qquad (6)$$

The Intelli Solar system is designed to be scalable, adaptable, and user-friendly, making it suitable for residential, commercial, and industrial applications. By combining multiple functionalities into a single platform, it provides a comprehensive solution for modern solar energy management.

B. System Architecture

The Intelli Solar system follows a structured architecture that organizes its components into different functional layers. This layered architecture ensures efficient data flow, modular design, and ease of system management is shown in Figure 2.

1) Sensing Layer

The sensing layer consists of all input devices responsible for collecting real-time data from the environment and the system. This includes light sensors, voltage sensors, and temperature sensors. These sensors continuously monitor conditions and provide raw data to the processing unit.

2) Processing Layer

The processing layer is the core of the system and includes the microcontroller or embedded system. It processes incoming data, executes control algorithms, and performs AI-based analysis. This layer is responsible for decision-making and system coordination.

3) Control Layer

The control layer consists of actuators and output devices such as motors, relay modules, and water pumps. Based on the decisions made by the processing layer, this layer performs physical actions such as adjusting panel orientation or activating the cleaning system.

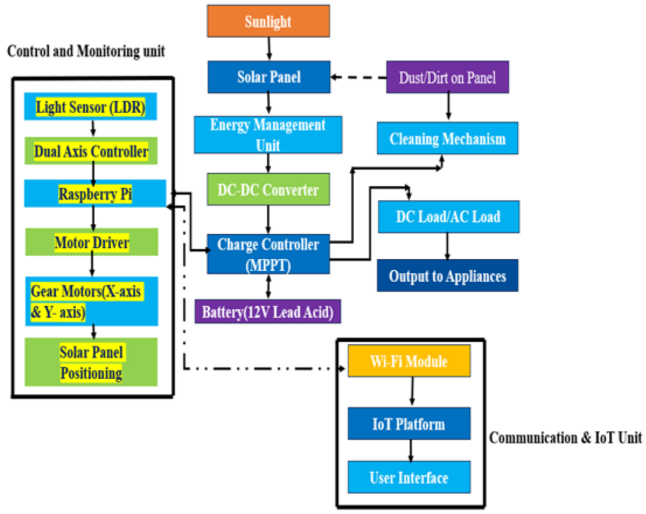

Figure 1. Block Diagram of Intelli Solar AI-Based Solar Energy Management System

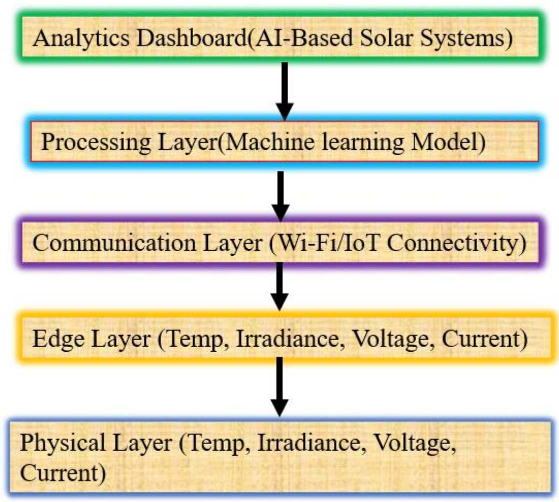

Figure 2. Layered Architecture of Intelli Solar AI-Based Solar Energy System

4) *Communication Layer*

The communication layer enables data transmission between the system and external platforms. It uses Wi-Fi or other communication technologies to send data to cloud servers or web dashboards. This layer ensures remote monitoring and control.

5) *Application Layer*

The application layer represents the user interface, typically in the form of a web dashboard. It displays system data, graphs, and alerts, allowing users to interact with and control the system. This layered architecture enhances system scalability, flexibility, and efficiency, making it suitable for various applications.

C. *Features of the System*

The Intelli Solar system incorporates several advanced features that significantly improve the performance and functionality of conventional solar systems.

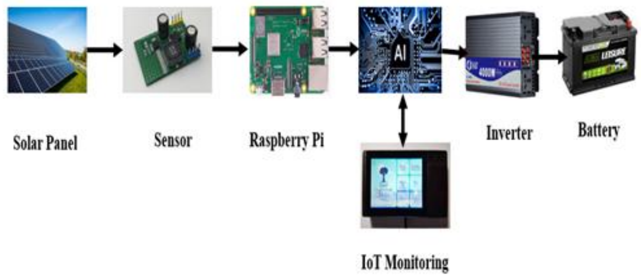

Figure 3. Functional Features of Intelli Solar AI-Based Solar systems

1) AI-Based Monitoring

The system utilizes artificial intelligence to analyze real-time data and provide intelligent insights. It can detect inefficiencies, predict potential failures, and recommend corrective actions, thereby improving system performance and reliability.

2) Dual-Axis Solar Tracking

The system includes a dual-axis tracking mechanism that adjusts the solar panel orientation both horizontally and vertically. This ensures maximum exposure to sunlight throughout the day and across different seasons, resulting in higher energy output.

3) Automated water Cleaning System

An automatic cleaning mechanism is integrated into the system to remove dust and dirt from the panel surface. This feature reduces manual maintenance efforts and helps maintain optimal efficiency.

4) Live Camera Monitoring

A camera module is included to provide real-time visual monitoring of the system. This enhances system security and allows users to remotely inspect the condition and operation of the solar setup.

5) Real-Time IoT Monitoring

The system continuously transmits data to a web-based dashboard, enabling users to monitor system performance in real time. This improves transparency and allows quick response to issues.

6) Smart Alerts and Notifications

The system generates alerts when abnormal conditions such as overheating, low efficiency or faults are detected. This helps in timely maintenance and prevents system damage.

7) Enhanced Energy Efficiency

By combining tracking, cleaning, and intelligent monitoring, the system ensures maximum energy generation and efficient utilization of solar power.

4. Architecture and Operation of the Proposed Model

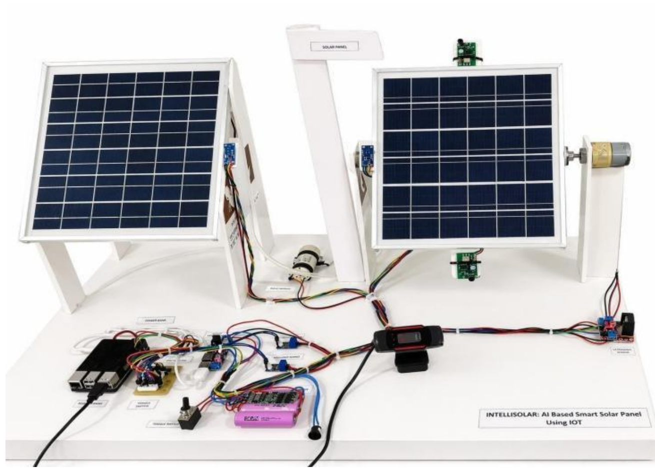

Figure 4. Prototype Model of Intelli Solar AI-Based Smart Solar Tracking System Using IoT

The solar panel (12V, 50–100W) generates DC power from sunlight. This power is fed into a solar charge controller, which regulates voltage, current and charges the battery safely, provides a stable 5V output for the Raspberry Pi. The battery acts as an energy storage unit, ensuring continuous operation during low sunlight or night conditions. The Raspberry Pi Central Control Unit (Raspberry Pi 3B+) acts as the main controller of the system. It receives input signals from sensors and sends control signals to actuators such as motors. It also handles IoT communication and data processing. A voltage sensor module is connected to the solar panel output. It scales down the voltage to a safe level for measurement. The analog signal is read (via ADC) by the Raspberry Pi to monitor panel performance. A BH1750 light sensor (I^2C based) measures ambient light intensity in lux. LDR sensors are arranged to detect sunlight direction. These sensors help determine the optimal orientation for the tracking system. In dual-axis solar tracking system two DC motors are used for X-axis and Y-axis movement. Each motor is controlled using an H-bridge motor driver. Based on sensor inputs, the Raspberry Pi sends signals to the motor drivers to rotate the panel towards maximum sunlight. Motor driver (H-Bridge) allows speed and direction control separate drivers are used for each axis of movement. A water pump (12V DC) is used for cleaning the solar panel. The pump is controlled through a relay module connected to the Raspberry Pi when activated, water is sprayed to remove dust and improve efficiency is shown in Figure 4.

A. Solar Energy Generation

The system consists of two photovoltaic (PV) panels: a stationary panel and a tracking panel. When solar radiation falls on the panels, it is converted into DC electrical energy through the photovoltaic effect. The stationary panel remains fixed, while the tracking panel dynamically adjusts its orientation to maximize solar irradiance, resulting in improved energy generation.

B. Sensing and Data Acquisition

The system continuously monitors key parameters using multiple sensors. Voltage sensors measure the electrical output of both panels. BH1750 sensors measure ambient light intensity. Temperature sensors monitor system thermal conditions. All sensor data is periodically acquired (approximately every 5 seconds) by the Raspberry Pi, ensuring real-time monitoring of system performance.

C. Signal Processing and Conversion

Since the Raspberry Pi does not support direct analog input, the analog voltage signals are converted into digital form using a high-resolution ADC (ADS1115). The collected data is then calibrated and normalized to ensure accurate analysis and visualization.

D. Solar Tracking Mechanism

The tracking system uses light intensity differences detected by sensors (LDR/BH1750) to determine the direction of maximum sunlight. Based on this information, a DC geared motor or actuator adjusts the panel orientation along one or two axes. This continuous adjustment ensures that the panel remains aligned with the sun throughout the day, thereby increasing energy efficiency compared to the stationary panel.

E. Data Logging and Storage

All processed data, including voltage, light intensity, and temperature, is stored in a structured SQLite database along with timestamps. This enables historical data analysis, performance comparison and trend identification over time.

F. IoT-Based Monitoring and Dashboard

A web-based dashboard is developed using Flask, allowing real-time monitoring of system parameters. The dashboard displays voltage, light intensity, and temperature. It also shows graphical trends using charts and provides comparative analysis. between stationery and tracking panels. Data is updated periodically using API calls, enabling remote monitoring from any connected device.

G. AI-Based Intelligent Analysis

An embedded AI module analyzes recent sensor data to evaluate system performance. The AI performs efficiency comparison between panels, detection of voltage fluctuations, identification of environmental changes such as cloud cover, prediction of maintenance needs (dust accumulation). Based on this analysis, the system generates real-time insights and alerts to improve operational efficiency.

H. Automated Cleaning Mechanism

To maintain optimal performance, the system includes a water pump-based cleaning mechanism. When required (either manually or based on system conditions), the pump sprays water onto the panel surface to remove dust and debris, thereby improving light absorption and efficiency.

I. Continuous Operation Cycle

The entire system is shown in Figure 5 operates in a continuous loop. The process steps include solar panels generate energy, sensors collect real-time data, data is processed and converted Tracking system adjusts panel orientation, data is stored and transmitted to the dashboard, AI analyzes performance and generates insights.

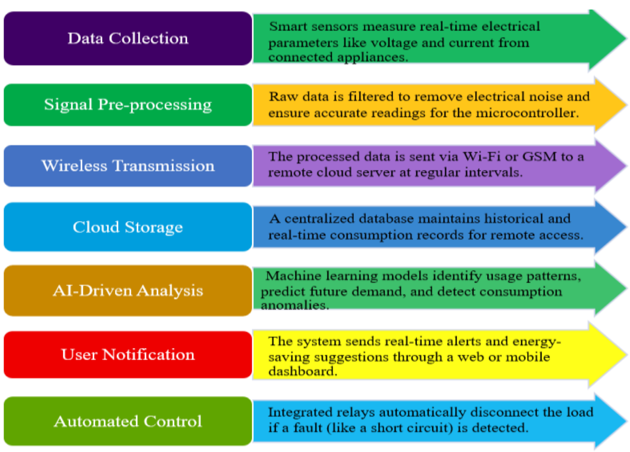

Figure 5. Operation of the Proposed Model

5. Intelli Solar Dashboard Overview

The Intelli Solar dashboard provides a real-time monitoring interface for the solar system using IoT is shown in Figure 6. It displays key performance parameters such as voltage, light intensity, and temperature, along with graphical analysis and system status. Displays voltage and light intensity obtained from the fixed solar panel. It shows system status fluctuations, indicating variations in output due to environmental conditions. It is used as a reference to compare performance with the tracking panel. Temperature monitoring displays the system temperature (≈39.2°C) in real time. It helps monitor thermal conditions and prevents overheating of component. Light intensity graph shows variation of light intensity over time for both panels. Helps analyze sunlight availability and effectiveness of tracking. Differences between curves indicate improved light capture by the tracking panel. Real time data is updated periodically through IoT communication via API calls. Ensures continuous monitoring and accurate system status.

Overall functionality dashboard integrates data visualization, real-time monitoring, and comparative analysis, enabling users to evaluate system performance, detect issues, and optimize solar energy utilization.

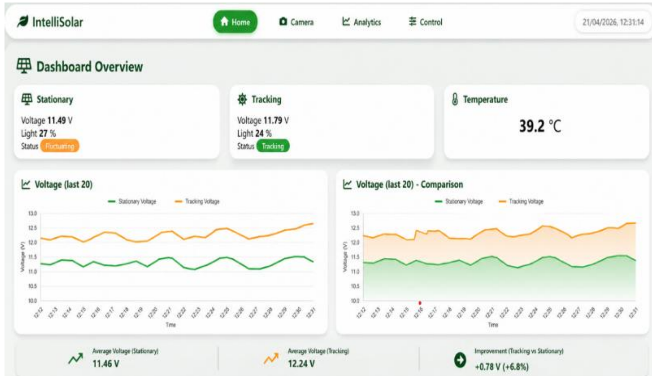

Figure 6. Solar System Dashboard for Real-Time Monitoring and Analytic

Table 1. Summary of Dashboard Parameters and Voltage Statistics (Most recent 20 Samples)

Parameter	**Stationary Mode**	**Tracking Mode**	**Difference**
Voltage (V)	11.49	11.79	+0.30
Light Intensity (%)	27	24	−3
Status	Fluctuating	Tracking	---
Temperature (°C)	39.2	39.2	0

The comparative operational performance of the tracking and stationary modes in the suggested Intelli Solar system is shown in Table 1. Improved photovoltaic energy conversion through ideal sun alignment was demonstrated by the tracking mode's higher output voltage of 11.79 V as opposed to 11.49 V during stationary operation. The clever tracking mechanism maintained effective incident angle positioning, improving electrical production even when the measured light intensity dropped marginally from 27% to 24%. While the tracking mode guaranteed steady performance, the stationary mode displayed erratic behaviour. Under both circumstances, the temperature was maintained constant at 39.2°C, indicating that the tracking approach rather than thermal impacts was the main cause of the voltage enhancement.

Table 2. Statistical Summary

Metric in Volt	**Stationary**	**Tracking**	**Difference**	**% Improvement**
Mean	11.352	12.246	+0.893	7.82%
Std. Deviation	0.066	0.062	0.072	0.61%
Minimum	11.262	12.092	+0.712	6.24%
Maximum	11.456	12.313	+0.981	

In the suggested Intelli Solar system, the voltage performance of tracking and stationary modes is illustrated in Table 2. The tracking mode outperformed the stationary mode by 7.82%, with a mean voltage of 12.246 V as opposed to 11.352 V. Enhanced solar energy harvesting was indicated by greater minimum and maximum voltage levels during tracking operation.

Table 3. System component list and specifications

Component	**Specification**	**Parameter**
Solar Panel	12V,50-100W	Generate DC power from Photon

Battery	12V,7Ah (Lead Acid)	Store energy
Charge Controller	12V/10A,5V	Provide stable 5V to Raspberry Pi
Raspberry Pi	Raspberry Pi 3B+	Data Processing, IoT communication
Voltage Sensor	0-25V DC	Monitors panel voltages
LDR Sensors	4*LDR Array	Tracking sunlight direction
BH1750 Sensor	1-65535 lux	Measure light intensity
Motor Driver	L298N(H-Bridge)	Speed and direction control of DC motor
DC Motors	12V,100 RPM	X-axis, Y-axis movement measurement
Water Pump	12V DC	For Cleaning solar panel surface
Relay Module	1 Channel,12V	Controls water pump

Table 3 summarizes the hardware components used in the proposed Intelli Solar system. The Raspberry Pi 3B+ carries out control, IoT connectivity, and data processing tasks. For intelligent tracking, voltage and light sensors track the performance of panels and the amount of sunshine. The water pump with relay module allows for automated surface cleaning of the solar panels, and the L298N motor driver regulates the dual-axis DC motors for panel movement.

Table 4. Sensors Readings on different climate condition

Condition	**Light Intensity(lux)**	**Panel Voltage (V)**	**Panel Power (P) (W)**
Low Sunlight	514	11.04	5.64
Medium Sunlight	15,436	13.5	28.74
High Sunlight	53,983	16.98	78.45

The performance of solar panels under various sunlight situations is displayed in Table 4. The panel voltage rose from 11.04 V to 16.98 V as light intensity climbed from 514 lux to 53,983 lux, and power generation greatly improved from 5.64 W to 78.45 W. The findings demonstrate that increased sun irradiation improves photovoltaic production and the Intelli solar system's total energy harvesting efficiency.

Table 5. Operating condition of motor (both the axis)

Axis	**Parameter**	**Minimum**	**Maximum**
X-axis Motor	Speed (RPM)	20	112
	Current (A)	0.19	0.93
Y-axis Motor	Speed (RPM)	20	108
	Current (A)	0.17	0.89

The X-axis and Y-axis DC motors used in the dual-axis solar tracking mechanism of the suggested Intelli Solar system are described in Table 5.While the Y-axis motor reached speeds between 20 RPM and 108 RPM and consumed 0.17 A to 0.89 A, the X-axis motor ran between 20 RPM and 112 RPM with a current consumption ranging from 0.19 A to 0.93 A.

Adaptive movement of the solar panel in response to tracking requirements and sunlight direction is indicated by variations in motor speed and current. Larger positional changes were associated with higher motor speeds and current values, while constant or limited tracking movement was associated with lower values. The outcomes show effective motor performance with low power consumption, guaranteeing precise dual-axis panel placement and increased solar energy harvesting effectiveness.

Table 6. Generated Electrical Parameter Summary

Parameter	Maximum Value	Minimum Value	Average Value
Panel Voltage (V)	10.32	18.84	14.34
Panel Current (A)	0.22	5.48	2.62
Panel Power (W)	2.44	94.86	37.39
Controller Output Voltage (V)	4.93	5.09	5.02
Battery Charging Current (A)	0.13	4.92	1.93
Battery Voltage (V)	11.34	13.78	12.46

The electrical performance metrics of the suggested Intelli Solar system are compiled in Table 6. Panel current ranged from 0.22 A to 5.48 A, and panel voltage ranged from 10.32 V to 18.84 V with an average of 14.34 V. With an average output power of 37.39 W and a maximum power of 94.86 W, the generated electricity demonstrated efficient photovoltaic energy harvesting. For dependable Raspberry Pi operation, the controller kept the output voltage steady at about 5.02 V. Furthermore, consistent charging and effective energy management within the Intelli Solar system were confirmed by the battery charging current and voltage, which ranged from 0.13 A to 4.92 A and from 11.34 V to 13.78 V, respectively.

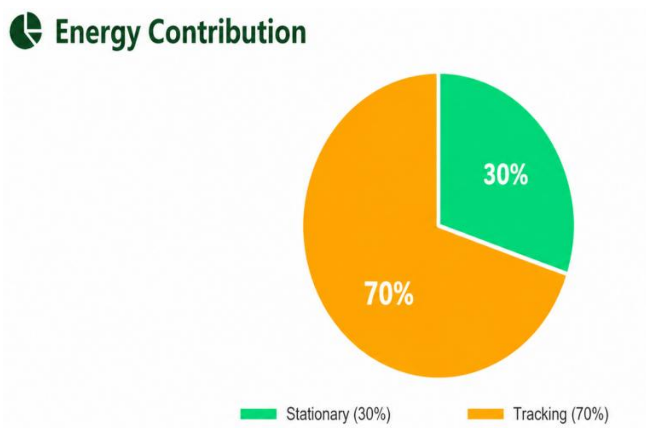

Figure 7. Energy contribution comparison between stationary and tracking solar systems

The proposed Intelli Solar system's comparative performance evaluation in stationary, tracking, and tracking with cleaning operating modes is shown in Table 7. By raising the average panel voltage from 12.5 V to 16.2 V and the power output from 23.92 W to 49.7 W, the dual-axis tracking system greatly improved photovoltaic performance, resulting in an efficiency gain of 108.9% over stationary operation. An additional improvement of 119.5% was attained by integrating the automated cleaning mechanism, where the tracking with cleaning mode produced a maximum average power of 52.34 W and daily energy generation of 1256.5 Wh/day. The outcomes confirm that intelligent tracking and automated maintenance can increase solar energy harvesting efficiency and system reliability.

Figure 8. Voltage variations comparison of stationary and tracking solar panels over time

The voltage graph represents the variation in output voltage of both the stationary and tracking solar panels over time (last 20 readings). The tracking panel exhibits higher voltage peaks compared to the stationary panel, indicating improved solar energy capture due to continuous alignment with the sun is depicted in Fig 8. This demonstrates the effectiveness of the tracking mechanism in enhancing power output. The stationary panel shows relatively lower and more stable voltage, as it remains fixed and receives varying sunlight depending on the sun’s position. Fluctuations observed in both curves are due to environmental factors such as cloud movement, shading, and changes in solar irradiance. Sudden spikes in the tracking panel indicate moments of optimal alignment with maximum sunlight is presented in Figure 9.

Figure 9. Generated solar power over time

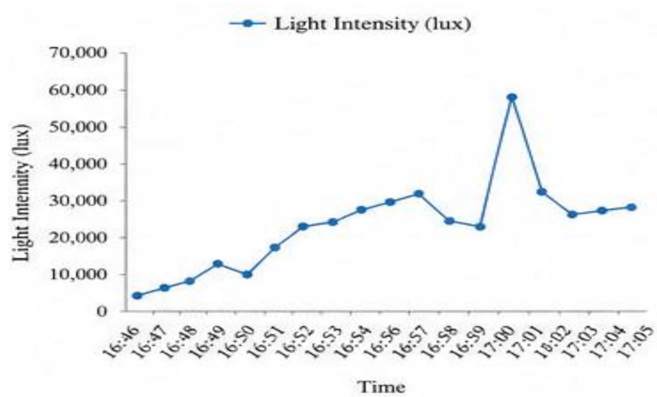

Figure 10. Light intensity comparison of stationary and tracking solar panels over time

The light intensity graph in fig 10 represents the variation of incident solar radiation for both the stationery and tracking panels over time (last 20 readings). The tracking panel exhibits higher light intensity values during certain intervals, indicating its ability to align with the direction of maximum sunlight. This confirms the effectiveness of the tracking mechanism in capturing more solar irradiance. The stationary panel shows comparatively lower or delayed peaks, as it remains fixed and cannot continuously adjust to the sun’s position. The alternating peaks between the two curves indicate the movement of the tracking system, where the panel reorients itself to follow the sun, resulting in improved light capture at different time instances. Sudden drops in intensity for both panels represent temporary environmental changes, such as cloud cover or shading.

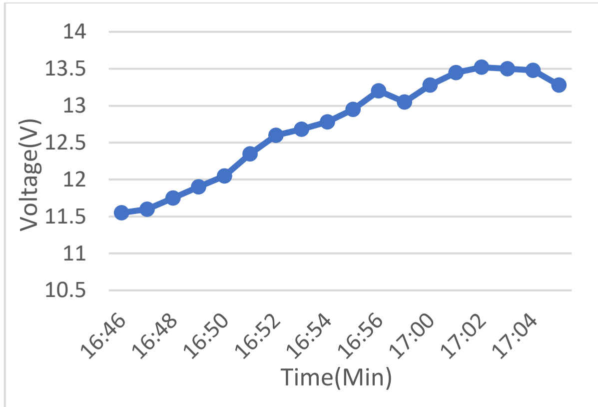

Figure 11. Battery voltage vs time

The battery voltage variation over time in the suggested Intelli Solar system is presented in Fig. 11. Stable battery charging and effective solar energy transmission are indicated by the voltage rising from roughly 11.5 V to 13.5 V. The system operates steadily within the safe charging range despite slight variations brought on by fluctuating solar irradiation.

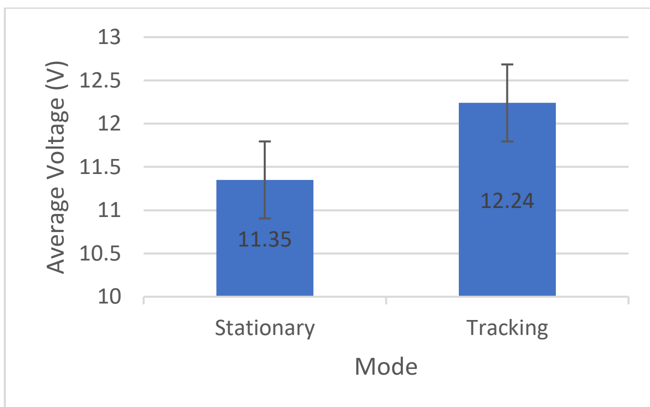

Figure 12. Average voltage comparison of stationary and tracking solar panels

The tracking panel exhibits higher light intensity values during certain intervals, indicating its ability to align with the direction of maximum sunlight. This confirms the effectiveness of the tracking mechanism in capturing more solar irradiance. The average voltage comparison between the Intelli Solar system's tracking and stationary modes is shown in Fig.12. Improved solar energy harvesting efficiency is seen by the tracking mode's higher average voltage of 12.24 V as opposed to 11.35 V in stationary mode. The dual-axis tracking mechanism's improved alignment with sunlight is confirmed by the voltage rise, which improves photovoltaic output performance. The stationary panel shows comparatively lower or delayed peaks, as it remains fixed and cannot continuously adjust to the sun's position.

A. Libraries Used

Python is the primary programming language used in the Intelli Solar system due to its simplicity, versatility, and extensive support for hardware interfacing, web development, and data analysis. Python provides a high-level programming environment that allows rapid development and easy integration of different system components. One of the key advantages of Python is its readability and modular structure, which makes it suitable for developing complex systems like Intelli Solar. It supports multiple programming paradigms, including procedural, object-oriented, and functional programming, enabling flexible system design. In this paper, python platform is used for:

- Interfacing with hardware components such as sensors, relays, and motors.
- Collecting and processing real-time data from the system.
- Implementing IoT communication and web server functionality.

- Integrating AI-based analysis for performance optimization.
- Handling camera operations and video streaming.

Additionally, Python runs efficiently on platforms like Raspberry Pi, making it an ideal choice for embedded and IoT-based applications. Its large ecosystem of libraries and frameworks significantly reduces development time and enhances system capabilities.

1) *OpenCV (cv2)*

OpenCV is used for handling camera operations and image processing. It enables capturing video frames, encoding them, and streaming live video through the web dashboard. This library is essential for implementing live camera monitoring feature.

Table 7. Systems operation modes and performance

Mode	**Tracking Status**	**Average light Intensity (lux)**	**Average Panel Voltage (V)**	**Average Panel Power(W)**	**Energy Generated (Wh/day)**	**Efficiency Improved**
Stationary Mode	Fixed Position	18.5	12.5	23.92	573.9	-----
Tracking Mode	Dual Axis Tracking	32.9	16.2	49.7	1192.2	108.9%
Tracking + Cleaning Mode	Dual Axis Tracking + Pump	33.2	16.34	52.34	1256.5	119.5%

2) *Flask*

Flask is a lightweight web framework used to create the web dashboard and API endpoints. It allows the system to serve web pages, handle HTTP requests, and provide real-time data to users. Flask is used to build routes for displaying sensor data, controlling devices, and streaming video.

3) *RPi. GPIO / GPIO Libraries*

These libraries are used for interfacing with the GPIO pins of the Raspberry Pi. They allow the system to control hardware components such as relays, motors, and sensors by sending digital signals.

4) *SQLite3*

This library is used to manage the local database for storing sensor readings and system data. It enables efficient data storage and retrieval.

5) *NumPy*

NumPy is used for numerical operations and data handling, especially in image processing and data analysis tasks.

6) *Threading*

The threading module is used to perform multiple tasks simultaneously, such as continuous sensor data logging and web server execution.

7) *Time and Datetime*

These libraries are used for scheduling tasks, managing time intervals, and recording timestamps for data logging. These libraries work together to create a fully functional system that integrates hardware control, data processing, and user interaction.

8) *Database System (SQLite)*

SQLite is used as the database system in the Intelli Solar project for storing and managing system data. The energy contribution chart represents the proportion of total power generated by the stationary and tracking solar panels. The tracking panel contributes a larger share of the total energy output compared to the stationary panel presented in Fig 7. This indicates that the tracking mechanism effectively aligns the panel with the sun, allowing it to receive higher solar irradiance throughout the day. As a result, the tracking panel achieves improved energy conversion efficiency. The comparatively lower contribution from the stationary panel highlights the limitations of fixed orientation, where the angle of incidence varies with time, reducing energy capture.

6. Conclusion

In this work to improve solar energy harvesting, introduced Intelli Solar, an AI-enabled smart photovoltaic monitoring and dual-axis solar tracking system built on the Internet of Things and Raspberry Pi. The suggested framework effectively combined wireless monitoring, intelligent maintenance, automatic panel orientation control, and real-time sensing into a single scalable platform. Dynamic solar tracking considerably increases panel output when compared to stationary operation, according to experimental data. The tracking mode produced an average voltage of 12.24 V, which was 7.82% higher than the stationary mode's 11.35 V. In a similar vein, average power generation rose by about 18.6%, proving the value of ideal solar alignment. Long-term system reliability was enhanced and dust-related efficiency losses were further minimised by the automated cleaning process. Predictive performance monitoring, anomaly detection, and intelligent maintenance recommendations were made possible by AI-based analytics, which reduced operational downtime. Real-time decision assistance and continuous remote monitoring were made possible via IoT connected web-based dashboard.

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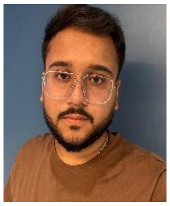

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