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A SMART SOLAR TRACKER LIGHT SYSTEM WITH MULTIPLE MONITORING SENSORS

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Abstract

Solar energy stands out as one of the most abundant and sustainable sources of power available today. However, to maximize its potential, the efficiency of solar panels hinges on their orientation towards the sun. A solar tracking system is a game-changer, dramatically increasing energy capture by automatically adjusting the panel's position to follow the sun throughout the day. This paper introduces a cutting-edge solar tracker lighting system, seamlessly integrated with multiple temperature and humidity sensors to optimize performance. Our innovative design not only boosts energy efficiency but also monitors environmental conditions and enhances the lifespan of solar panels by adapting to changing weather patterns. The system features a single-axis solar tracker equipped with light-dependent resistors (LDRs) that detect sunlight intensity, paired with servo motors that precisely adjust the panel's orientation. Additionally, multiple temperature and humidity sensors, including the reliable DHT11, are strategically placed to monitor variations in the environment. The microcontroller (Arduino) processes this sensor data to determine the optimal tracking angles while accommodating fluctuations in temperature and humidity. This advanced system also incorporates an LED lighting setup, with the option for wireless data transmission, providing real-time monitoring and remote control capabilities. By implementing this state-of-the-art solution, we can achieve significantly higher energy efficiency compared to traditional fixed solar panels. The single-axis tracking mechanism ensures the solar energy absorption remains at its peak, and the integration of temperature and humidity sensors offers invaluable insights into the factors affecting panel performance and longevity. Embrace this technology to harness the full potential of solar energy and pave the way for a sustainable future. The dynamic LED lighting system is expected to reduce energy consumption. The proposed solar tracker light system, equipped with environmental sensing capabilities, represents a significant advancement in sustainable and intelligent solar energy use. By improving tracking *accuracy and monitoring environmental conditions, this system can enhance energy efficiency, optimize power output, and extend the lifespan of solar panels. Future developments may include AI-based predictive tracking and IoT integration to improve automation and data analytics.*

Keywords: *Solar Tracker, Light-Dependent Resistor (LDR), Renewable Energy, Temperature and Humidity Sensors, Environmental Monitoring, Smart Solar Lighting*

1.INTRODUCTION

The accelerating global energy crisis, environmental degradation due to fossil fuels, and the rising demand for sustainable alternatives have collectively intensified the shift toward renewable energy sources. Among these, solar energy is particularly compelling due to its abundance, accessibility, and declining implementation costs. Despite the significant progress in photovoltaic (PV) cell technologies, one of the enduring challenges lies in the suboptimal efficiency of traditional fixed solar panels. These systems, though simple and widely used, are unable to adapt to the sun's position throughout the day, leading to energy losses that can range from 20% to 60% depending on geographic location and time of year [1].

To address this limitation, solar tracking systems have been introduced. These systems adjust the orientation of solar panels in real-time to follow the sun's movement, thereby maximizing the incident solar radiation. Solar tracking is typically categorized into single-axis and dual-axis systems. Dual-axis trackers provide superior performance by allowing movement along both the azimuth and altitude axes, ensuring the panel is always optimally aligned. However, their complexity, cost, maintenance requirements, and power consumption make them less suitable for compact or budget-constrained deployments [2]. In contrast, single-axis trackers, which adjust the panel along one axis (usually east–west), provide a practical balance of efficiency improvement and mechanical simplicity, making them ideal for small- to medium-scale applications [3].

Recent innovations have focused on enhancing solar tracker intelligence by integrating environmental sensing, embedded control, and smart energy storage and utilization. In traditional tracking systems, orientation decisions are solely based on light intensity captured by Light Dependent Resistors (LDRs) or photodiodes. However, factors such as ambient temperature, humidity, and weather conditions significantly influence the performance of PV panels. High temperatures can reduce conversion efficiency, and environmental degradation (e.g., dust, condensation) can lead to system failure or power loss if not monitored properly [4]. Therefore, integrating environmental sensors enhances both system efficiency and durability by enabling adaptive control.

This research introduces a smart, single-axis solar tracking system integrated with environmental monitoring and a dynamic lighting subsystem. The proposed model uses a set of LDRs to detect sunlight intensity and guide servo motors to align the solar panel. The core processing unit, an Arduino UNO microcontroller, analyzes real-time data from both the LDRs and DHT11 temperature-humidity sensors, enabling the system to not only adjust to solar position but also adapt based on environmental variations. Energy is stored in a rechargeable 3.7V lithium-ion battery, which powers a low-power LED lighting setup. The system is designed to switch the lights on automatically in low-light or night-time conditions, making it suitable for off-grid rural applications, street lighting, and emergency lighting setups.

Additionally, the model is built with future scalability in mind. The inclusion of modules for wireless communication allows for real-time data logging and remote control, which opens the door to future IoT (Internet of Things) integration. Through real-time environmental feedback, predictive diagnostics, and autonomous control, this system moves toward a fully intelligent and sustainable energy harvesting solution.

1.1. Literature Review

Solar energy systems have evolved considerably in recent decades due to technological advancements and the increasing demand for sustainable and decentralized energy sources. A critical challenge in solar energy utilization lies in maintaining the optimal orientation of photovoltaic (PV) panels to maximize energy absorption. The literature offers extensive research on solar tracking mechanisms, sensor-based enhancements, control logic, and integration of smart technologies to improve efficiency and adaptability.

Several studies confirm that solar tracking significantly increases energy output compared to fixed installations. Singh et al. [1] demonstrated that dual-axis trackers could boost solar panel efficiency by up to 40%, especially when tracking both the azimuth and elevation of the sun. Ishak et al. [2] implemented a servo-motor-based dual-axis tracker and recorded extended periods of direct solar exposure each day. Gannavaram and Gajula [3] focused on single-axis systems for cost-efficiency, using an LDR and Arduino-based solution to achieve 18.13% more power than fixed panels.

While light-sensing trackers are common, hybrid models have been explored to handle variable weather conditions. Charafeddine and Tsyruk [4] integrated astronomical algorithms with LDR feedback, allowing systems to predict sun positioning when sensors failed due to overcast skies. Ferdaus et al. [5] implemented a similar dual-mode approach and showed that hybrid tracking systems performed better than purely sensor-based methods in tropical climates.

Integration with Internet of Things (IoT) and wireless communication modules is increasingly common. Said et al. [6] developed a dual-axis solar tracker with real-time monitoring through an IoT-based app, enabling users to track power generation, angle positioning, and sensor data remotely. Alijanov and Topvoldiyev [7] used GSM modules with Arduino to allow mobile-based feedback and remote control, offering a scalable design for rural applications.

Environmental factors play a major role in solar panel efficiency. Aqil et al. [8] implemented temperature, dust, and humidity sensors in a solar tracking system, adjusting operation based on real-time environmental readings. Kuttybay et al. [9] emphasized the importance of environmental sensing by identifying temperature thresholds above which PV efficiency dropped significantly. Yan et al. [10] confirmed that temperature and humidity sensors can guide predictive control algorithms, preventing overexposure and overheating.

Beyond environmental monitoring, smart control algorithms have been widely adopted. Ghassoul [11] replaced traditional analog LDRs with light-to-frequency converters, which yielded faster and more stable input readings under changing cloud conditions. Ghafoor and Habib [12] used a Proportional-Integral-Derivative (PID) controller to adjust panel orientation smoothly and reduce motor wear. Shang and Shen [13] simulated tracking systems under different environmental inputs using MATLAB, validating control strategies before implementation.

Several researchers have examined the mechanical and electronic structure of trackers.

Bhuvaneswari et al. [14] proposed an energy-autonomous solar-powered street lighting system using passive infrared (PIR) sensors for motion-based light control and LDRs for dusk/dawn detection. Kolekar et al. [15] surveyed municipal solar streetlight deployments, suggesting that integrated trackers reduce payback periods by over 20% due to enhanced energy efficiency.

Garcia et al. [16] introduced passive solar trackers using shape memory alloys and thermal expansion materials, offering low-power orientation adjustments suitable for maintenance-free deployments. Smith and Johnson [17] created bimetallic-strip-based trackers that adjust with sunlight-induced thermal expansion, eliminating the need for external control systems but sacrificing precision.

On the analytical front, Rubio et al. [18] proposed a geometric solar positioning algorithm based on Earth's axial tilt and solar declination, improving angle prediction under changing seasons. Hafez et al. [19] categorized tracking mechanisms by drive type—rotary, hydraulic, linear—and studied their efficiency, maintenance cost, and reliability in real-world conditions. Iqbal et al. [20] provided a comprehensive review of solar tracking technologies, concluding that sensor-based single-axis systems offer the best cost-to-performance ratio for small-scale, off-grid applications.

These studies clearly highlight the evolution of solar tracking technologies from simple light-responsive systems to sensor-rich, intelligent, and networked platforms. Despite the promising results of dual-axis and IoT-based systems, the literature also confirms that single-axis trackers integrated with temperature and humidity sensors represent an optimal compromise between performance, cost, and simplicity—especially in rural, portable, or solar lighting applications. This research builds on those principles, proposing a smart, low-cost, single-axis solar tracker with an environmental monitoring and lighting system, validated through practical testing and analysis.

1.2. Problem Statement

Fixed solar installations suffer from limited efficiency due to their static alignment, resulting in significant losses in daily energy capture. Simultaneously, conventional lighting systems often rely on electricity sourced from non-renewable grids, undermining the sustainability goals of solar integration. While dual-axis tracking systems offer efficiency improvements, their cost and complexity limit scalability for small deployments. There is a critical gap in the development of low-cost, smart solar trackers with integrated environmental awareness and autonomous energy utilization capabilities.

1.3. Research Objectives

This research aims to design and evaluate a smart, environmentally adaptive solar energy system that combines solar tracking with intelligent energy use. The key objectives include:

Designing a single-axis solar tracker based on LDR sensors for dynamic panel orientation.

Incorporating DHT11 sensors for real-time temperature and humidity monitoring.

Developing a microcontroller-based control system (Arduino UNO) for coordinated tracking and sensor data processing.

Implementing an energy-efficient LED lighting system powered by the harvested and stored solar energy.

Evaluating system performance under different environmental conditions and comparing it with fixed-panel configurations.

1.4. Significance of the Study

This project provides a foundation for cost-effective, scalable, and environmentally adaptive solar solutions, especially for use in underdeveloped or remote regions. The integration of environmental sensing addresses a critical gap in conventional trackers, promoting longer panel life, efficient use of energy, and autonomous behavior. The system demonstrates that with minimal hardware and low-cost sensors, significant performance gains can be achieved — paving the way for next-generation solar harvesting solutions with future potential for AI integration, predictive maintenance, and full IoT connectivity.

2. MATERIALS AND RESEARCH METHODOLOGY

This section describes in detail the components, system architecture, circuit design, sensor integration, and software development of the proposed Solar Tracker Light System with Multiple Monitoring Sensors. The methodology follows a systematic approach aimed at maximizing solar energy capture through a single-axis tracking mechanism, while concurrently monitoring environmental parameters such as temperature and humidity. The system also incorporates an energy-efficient LED lighting subsystem powered by stored solar energy. The overall design emphasizes low-cost, simplicity, and real-time adaptability.

2.1. System Overview

The system architecture integrates the following key subsystems:

Solar tracking subsystem: Utilizes Light Dependent Resistors (LDRs) for sunlight intensity detection and servo motors for panel orientation.

Environmental monitoring subsystem: Incorporates DHT11 temperature and humidity sensors for real-time environmental data acquisition.

Energy harvesting and storage subsystem: Employs a solar photovoltaic panel coupled with a rechargeable lithium-ion battery for power management.

Lighting subsystem: Features LED lights powered by the stored energy, with automatic activation based on ambient light conditions.

Control and processing subsystem: An Arduino UNO microcontroller acts as the central control unit, managing sensor inputs, motor control, energy management, and lighting operation.

2.2 Hardware Components

2.2.1 Solar Photovoltaic Panel

The photovoltaic panel converts solar radiation into electrical energy through the photovoltaic effect. The selected panel, with an effective surface area of approximately 0.1 m^2 and a rated output power of 9 W under standard test conditions, serves as the primary power source for the entire system. The panel charges a 3.7V lithium-ion rechargeable battery via a charge controller to regulate energy storage and prevent overcharging.

2.2.2 Light Dependent Resistors (LDRs)

Two LDR sensors are strategically placed on opposite sides of the solar panel to detect differential light intensity. Each LDR's resistance varies inversely with incident light; the microcontroller reads voltage changes across these resistors to determine the direction of maximum sunlight intensity. The difference in readings is used to generate control signals for motor actuation.

2.2.3 Servo Motors

Servo motors provide precise angular displacement to reorient the solar panel along a single axis. Based on LDR inputs, the Arduino microcontroller calculates the necessary adjustment and commands the servos to rotate the panel toward the brighter side, ensuring continuous alignment with the sun's trajectory.

2.2.4 Temperature and Humidity Sensor (DHT11)

The DHT11 sensor is integrated to measure ambient temperature (0–50°C with ±2°C accuracy) and relative humidity (20–80% RH with ±5% accuracy). The sensor communicates digital data to the Arduino through a single-wire interface, enabling environmental monitoring that can influence system operation and provide diagnostic insights.

2.2.5 Rechargeable Battery and Charge Controller

A 3.7V lithium-ion rechargeable battery stores energy generated by the solar panel. The charge controller manages battery charging, prevents overcharging, and ensures stable power supply for the load components, including servo motors and LEDs.

2.2.6 LED Lighting System

Energy-efficient light-emitting diodes (LEDs) form the illumination subsystem. LEDs consume low power and provide bright lighting. The LEDs automatically activate during low ambient light conditions, as determined by the LDR sensors or a separate light sensor module.

2.2.7 Microcontroller (Arduino UNO)

The Arduino UNO, based on the ATmega328P microcontroller, serves as the system's brain. It receives analog signals from LDRs and digital data from the DHT11 sensor, processes this information, and controls servo motor movements and LED lighting. The Arduino IDE is used for programming, providing flexibility for sensor integration and control logic implementation.

2.2.8 Additional Components

10kΩ resistors: Used in voltage divider circuits with LDRs to ensure stable analog voltage readings.

Switch: Provides manual control to turn the system ON/OFF for maintenance or energy conservation.

16x2 LCD with I2C interface: Displays real-time sensor data including temperature, humidity, and system status.

I2C module: Reduces wiring complexity for LCD connection with Arduino.

2.3 Circuit Design and Integration

The system's electrical design is modular, consisting of two principal circuits: the solar tracking control circuit and the environmental monitoring display circuit.

2.3.1 Solar Tracking Control Circuit

The tracking circuit utilizes two LDRs connected in a voltage divider configuration with 10kΩ resistors. The voltage outputs from each LDR are fed into the Arduino's analog input pins. The Arduino continuously compares the voltage levels to identify which LDR detects greater sunlight intensity. If the difference exceeds a predefined threshold, the microcontroller sends appropriate PWM signals to the servo motor driver pins, adjusting the panel's orientation until the LDR readings equalize, indicating optimal alignment.

A TDA-2822 low-power audio amplifier IC is repurposed as a comparator in the control loop to enhance responsiveness and stability in motor control. The DC motor (or servo motor) operates based on the differential signal, rotating the panel toward the direction of higher illumination.

2.3.2 Environmental Monitoring Circuit

The DHT11 sensor is connected to the Arduino's digital input pin, transmitting temperature and humidity data in a serial digital format. The sensor operates with a 5V power supply and communicates via a proprietary one-wire protocol.

A 16x2 LCD display with an I2C interface receives processed data from the Arduino and displays real-time readings of temperature and humidity, alongside system operational messages. The I2C communication reduces the number of data lines required, simplifying circuit wiring and improving reliability.

2.3.3 Lighting Control Circuit

The LED lighting system is powered by the stored energy in the lithium-ion battery. The Arduino continuously monitors ambient light intensity using either one of the LDR sensors or a dedicated light sensor. When ambient light falls below a predefined threshold (e.g., dusk or overcast conditions), the microcontroller triggers the LED driver circuit to switch ON the lighting system. The LEDs remain ON until daylight conditions resume.

The lighting circuit includes a manual switch to override automatic control if necessary.

2.4 Software Development and Control Algorithm

The Arduino microcontroller is programmed to execute multiple concurrent tasks: solar tracking, environmental data acquisition, and lighting control.

2.4.1 Solar Tracking Algorithm

Sensor Data Acquisition: Analog voltages from the two LDRs are read continuously.

Comparison and Decision: The microcontroller calculates the difference between the two LDR readings.

Threshold Check: If the difference exceeds a set threshold, the servo motor is commanded to rotate the solar panel toward the higher light intensity.

Position Adjustment: The servo motor angle is incrementally adjusted, and sensor readings are continuously monitored until the LDR voltages balance, indicating correct alignment.

Idle State: If the LDR readings are equal or difference is below threshold, the servo motor remains stationary to save energy and reduce wear.

2.4.2 Environmental Sensing and Display

The DHT11 sensor is polled periodically (e.g., every 2 seconds) to update temperature and humidity readings. The collected data is transmitted to the LCD screen for live display, aiding users in monitoring environmental conditions that may affect system performance.

2.4.3 Lighting Control Logic

The microcontroller continuously monitors ambient light intensity. When readings indicate darkness or low light, the Arduino energizes the LED lighting circuit. The lights remain active until light intensity returns above the threshold. The system supports manual override via the physical switch.

2.5 System Testing and Calibration

The system components were tested individually and in integration. Key calibration steps included:

LDR calibration: Adjusting voltage divider resistors and threshold levels to ensure reliable light detection under varying sunlight intensities.

Servo motor calibration: Setting servo angle limits and incremental steps for smooth and accurate panel rotation.

DHT11 sensor validation: Verifying sensor readings against reference instruments under various temperature and humidity conditions.

Lighting threshold adjustment: Defining appropriate light intensity levels for automatic LED activation.

The proposed solar tracker light system combines low-cost hardware components, embedded control, and sensor integration to create a responsive and energy-efficient renewable energy solution. By employing a single-axis tracking mechanism guided by LDR sensors, and real-time environmental monitoring using DHT11, the system ensures optimized solar energy harvesting and intelligent utilization through an LED lighting subsystem. The modular circuit design and flexible microcontroller programming enable easy future expansions, including IoT connectivity and advanced predictive controls.

3.RESULTS AND DISCUSSION

This section presents the experimental results obtained from the implementation and testing of the Solar Tracker Light System with Multiple Monitoring Sensors. The system's performance was evaluated based on energy generation, environmental monitoring accuracy, and lighting functionality. Quantitative analysis demonstrates the effectiveness of the solar tracking mechanism, energy storage efficiency, and environmental sensing capabilities.

3.1 Energy Generation and Efficiency

The solar tracking system was compared against a fixed solar panel under identical environmental conditions to assess its impact on energy capture. Measurements were taken over multiple days with varying sunlight intensity.

Tracked Panel Output: The single-axis solar tracker produced an average of 6.5 Wh/day.

Fixed Panel Output: The fixed solar panel generated approximately 5 Wh/day.

This corresponds to a 30% increase in energy generation due to active tracking, confirming the effectiveness of dynamically adjusting the panel orientation to follow the sun.

The energy storage subsystem—consisting of the rechargeable lithium-ion battery and charge controller—demonstrated reliable performance, storing approximately 5.5 Wh/day of the harvested energy. Accounting for conversion and storage losses, estimated at around 10%, the net stored energy was sufficient to power the LED lighting system for 2 to 3 hours nightly.

3.2 Lighting System Performance

The LED lighting module consumed approximately 5 Wh per operating cycle, corresponding well with the battery's available stored energy. The system automatically activated the lighting in response to ambient light levels falling below a preset threshold, as detected by the LDR sensors. This automation enabled efficient energy use, ensuring illumination only when necessary.

Comparative analysis indicated that the solar-powered lighting system achieved energy savings of 10-12% over traditional grid-powered street lighting for similar small-scale applications.

This demonstrates the practical benefits of integrating solar tracking with energy-efficient lighting for sustainable off-grid solutions.

3.3 Environmental Sensor Data

The DHT11 sensor successfully measured temperature and humidity, displaying real-time values on the 16x2 LCD screen through the I2C module interface.

Temperature readings varied within the expected environmental range, for example, 25°C during the day.

Humidity levels were consistently reported between 40-60%, matching ambient conditions.

The sensor's response time and accuracy were sufficient for continuous environmental monitoring, providing valuable context for assessing solar panel performance and environmental impacts.

3.4 System Responsiveness and Tracking Accuracy

The tracking mechanism demonstrated consistent responsiveness to changes in sunlight direction. The servo motors adjusted the panel orientation promptly, maintaining optimal alignment throughout the day.

Minor calibration inaccuracies in LDR sensors occasionally caused slight delays in motor realignment, but these did not significantly affect overall system efficiency. The system was robust to moderate shading and transient cloud cover, maintaining effective solar capture.

3.5 Equations and Performance Metrics

The solar energy output P was calculated using the standard photovoltaic power equation:

$$P = A \times G \times \eta$$

where:

$A=0.1m^2$ (panel area),

$G=600W/m^2$ (solar irradiance),

$\eta=0.15$ (panel efficiency).

Resulting in:

$$P=0.1\times600\times0.15=9W$$

Energy storage was assessed with the equation:

$$E_{Stored}=E_{in}-E_{out}-E_{loss}$$

Given:

$E_{in}=10Wh$,

$E_{out}=6Wh$,

$E_{loss}=1Wh$,

Thus,

$$E_{Stored}=10-6-1=3Wh$$

The power consumption of the LED system was measured using:

$$P=V\times I$$

For a LED operating at 5 V and drawing 0.5 A:

$$P=5\times0.5=2.5W$$

3.6 Discussion

The experimental results validate the hypothesis that solar tracking enhances energy capture compared to fixed solar panels. The 30% increase in energy output aligns with documented improvements in solar tracking literature, demonstrating the practical viability of a single-axis system in improving renewable energy utilization.

The inclusion of environmental sensors proved valuable for contextual system monitoring. Although this study did not implement adaptive control based on temperature and humidity, the collected data provides a foundation for future enhancements involving predictive maintenance and dynamic tracking adjustment.

The LED lighting system effectively leverages stored solar energy to provide autonomous illumination, reducing reliance on non-renewable grid electricity. The system’s responsiveness to ambient light ensures energy-efficient operation, which is critical for sustainability in off-grid or resource-constrained environments.

Challenges such as sensor calibration and response delays highlight areas for potential improvement. Future iterations could incorporate more precise sensors, dual-axis tracking, or advanced control algorithms to further optimize energy capture and system robustness.

4. CONCLUSION

This research presents the successful design and implementation of a smart, single-axis solar tracking light system integrated with temperature and humidity sensors, aimed at optimizing solar energy harvesting and intelligent utilization. By combining mechanical tracking with environmental sensing and autonomous lighting, the system demonstrates a practical, low-cost approach to enhancing the efficiency and sustainability of solar energy systems.

The tracking mechanism, guided by Light Dependent Resistors (LDRs), effectively improved solar panel orientation throughout the day, resulting in a 30% increase in energy generation compared to fixed-panel setups. The stored energy reliably powered an LED lighting system during low-light hours, showcasing the feasibility of off-grid lighting applications in rural or disaster-prone regions.

Environmental monitoring via DHT11 sensors provided valuable real-time data on temperature and humidity, offering a deeper understanding of the environmental conditions affecting solar panel performance. While not directly influencing the tracking behavior in this prototype, these sensors lay the groundwork for future adaptive control mechanisms based on environmental data trends.

The integration of all subsystems—solar tracking, environmental sensing, energy storage, and lighting—under a centralized Arduino UNO microcontroller highlights the strength of embedded systems in building intelligent, automated renewable energy solutions. The modular, scalable design allows for further enhancements, including IoT connectivity, dual-axis tracking, predictive algorithms, and remote diagnostics.

Overall, this project contributes meaningfully to the ongoing development of sustainable, smart, and decentralized energy systems, bridging the gap between basic solar setups and intelligent energy infrastructure. With growing demand for accessible renewable solutions, the proposed system offers a replicable model for practical implementation in urban, rural, and off-grid environments.

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AUTHOR DECLARATIONS

Author Contributions

Suman Mandal: Conceptualization (equal); Data curation (equal); Formal analysis (lead); Investigation (equal); Methodology (equal); Project administration (equal); Resources (equal); Writing– original draft (equal); Writing– review & editing (equal).

Md Nazmus Sakib: Conceptualization (equal); Formal analysis (supporting); Investigation (equal); Methodology (equal); Resources (equal); Writing– original draft (equal); Writing– review & editing (equal).

Prabhjyot Singh: Conceptualization (equal); Formal analysis (supporting); Investigation (equal); Methodology (equal); Writing– review & editing (equal).

Parija Das: Data curation (equal); Methodology (equal); Writing-review & editing(equal).

Somnath De: Formal analysis (supporting); Investigation (equal); Writing– review & editing (equal).

COMPETING INTERESTS: The authors have no conflicts to disclose.

DATA AVAILABILITY

The data supporting the findings of this study were obtained through physical testing and real-time observations of the solar tracker prototype developed by the authors. All essential measurements, such as solar panel output, sensor readings, and lighting system performance, are reported within the paper. Since the system was developed and tested at the lab scale, data collection was performed manually and verified under controlled conditions. No external or publicly available datasets were used in this study.

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