



# A Survey on Smart Solar Tracker System with Smart Meter Integration using IoT

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**Abstract:** This paper presents the design and implementation of a modular and cost-effective solar energy solution integrating automatic single-axis tracking with an IoT-enabled smart metering system. The proposed system utilizes a 12V photovoltaic panel, a battery management system (BMS), and an ESP32 microcontroller to maximize solar energy harvesting. Solar tracking is achieved through a light-dependent resistor (LDR) and gear motor-based mechanism, ensuring optimal panel alignment with the sun's position throughout the day. The integration of current and voltage sensors enables the ESP32 to function as a smart energy meter, providing real-time monitoring of energy generation and consumption. Data is visualized locally via an LCD display and remotely transmitted through Wi-Fi to a cloud-based IoT platform. Experimental evaluation demonstrates that the system achieves improved energy yield compared to fixed solar panels and provides actionable insights for energy management, battery protection, and smart grid integration.

**Key Words:** Solar tracker, ESP32, Smart meter, IoT monitoring, LDR, Current sensor, Voltage sensor, Motor driver L298N, BMS.

## 1. INTRODUCTION

Global energy demands and the push for sustainability have accelerated the adoption of decentralized renewable energy sources like rooftop solar. However, the efficiency of fixed-tilt solar panels is significantly compromised as the sun's position changes throughout the day. Solar trackers address this by continually aligning the panel perpendicular to the sun's rays, substantially increasing the daily energy yield. Simultaneously, effective energy management requires real-time data on generation, storage, and consumption—the function of a smart meter. The Sun Solar Tracker System with Smart Meter Integration is an advanced renewable energy solution designed to maximize the efficiency and performance of solar power generation. In this system, a solar tracker automatically adjusts the position of solar panels to follow the sun's path throughout the day, ensuring that the panels receive maximum sunlight at all times. This project successfully merges these two concepts: an affordable single-axis solar tracker and an IoT-enabled smart meter, built upon the versatile ESP32 platform and low-cost sensors. This combined system offers an optimized micro-generation and monitoring solution ideal for off-grid or residential applications.

This significantly increases the energy output compared to fixed solar panel installations. The tracking mechanism is typically controlled using light sensors (LDRs) and a microcontroller or IoT-based controller, which determine the optimal angle for panel alignment. The smart meter integration adds an intelligent monitoring and control feature to the system. It enables real-time measurement of power generation, consumption, and grid interaction through sensors and wireless communication. The data collected by the smart meter can be transmitted to a cloud platform or mobile application, allowing users to monitor system performance, energy usage, and efficiency remotely. By combining solar tracking and smart metering, this system not only enhances energy generation but also promotes efficient power



management, cost savings, and sustainability. This makes it highly suitable for modern smart grid applications and eco-friendly energy systems.

This paper, whether you are a researcher, student, or developer, serves as a valuable tool for exploring the potential of solar energy systems and their integration with modern smart technologies. To illustrate the capabilities of solar innovation, we implement and analyze the Sun Solar Tracker System with Smart Meter Integration, a model demonstrating how intelligent tracking and real-time monitoring can significantly enhance energy efficiency. The solar tracker showcases the advantage of automatic sun tracking, maximizing energy capture through optimal panel alignment, while the smart meter highlights the importance of data-driven energy management in modern renewable setups. This study further emphasizes the real-world applications of solar automation and the crucial role such integrated systems play in promoting sustainable, efficient, and intelligent energy solutions for the future.

## **2.LITERATURE ANALYSIS**

Previous work in solar energy often focuses either on solar tracking for efficiency or on grid-tied smart metering. Low-cost tracking systems have historically employed microcontrollers (like Arduino/ESP) and LDR pairs for differential light sensing. IoT in solar systems primarily concentrates on large-scale PV farm monitoring. This project aims to bridge the gap by combining these elements into an integrated, small-scale, DC-powered system suitable for a portable or off-grid mini-project.

This section highlights some of the key contributions in the field of solar energy systems, with particular emphasis on how these advancements have evolved and shaped the development of solar tracking and smart metering technologies, as illustrated in TABLE I. It typically provides a summary of major contributions, categorized by their impact on the field—such as innovations in solar tracking mechanisms, improvements in photovoltaic efficiency, advancements in IoT-based energy monitoring, and the integration of smart metering for real-time data analysis. The tabular summary would further outline how each of these contributions has influenced subsequent research, enhanced system automation and efficiency, and helped establish the current state of intelligent solar energy management systems.

The literature is replete with numerous review papers that have made significant contributions to the field of solar energy systems. Such studies have conducted in-depth investigations into a wide range of technical topics, including solar tracking mechanisms, photovoltaic (PV) efficiency enhancement, IoT-based smart metering, energy optimization algorithms, and other related areas. However, the major drawback of most existing research is that many papers are either highly technical and complex, making them difficult for beginners to follow, or they fail to discuss the practical integration and real-world applications of these technologies. Furthermore, much of the available literature is written primarily for readers from electrical or renewable energy engineering backgrounds, leaving a gap for a broader audience.

This study addresses these limitations by presenting the Sun Solar Tracker System with Smart Meter Integration in a simplified and comprehensive manner, supported with diagrams and tables for better understanding. No prior technical expertise is required to grasp the concepts discussed. The paper provides an overview of the essential tools, technologies, and innovations driving the advancement of smart solar systems, while also highlighting key developments and offering insights into potential future directions for interested readers.

## **3.SYSTEM ARCHITECTURE**

The Sun Solar Tracker System with Smart Meter Integration is designed around a three-layered architecture consisting of the Sensing Layer, Control/Processing Layer, and Communication/Display Layer. These layers work together seamlessly to achieve efficient solar tracking, intelligent energy management, and real-time data monitoring. At the foundation lies the Sensing Layer, which is responsible for gathering all the essential data required for decision-making. The system uses a combination of voltage and current sensors to measure the electrical parameters of the solar panel, battery, and load. Additionally, Light Dependent Resistors (LDRs) are strategically placed to detect sunlight intensity and direction. These LDRs form the basis of the tracking mechanism, allowing the system to determine the position of the sun at any given time. The Control and Processing Layer is centered around the ESP32 microcontroller, which acts as the brain of the entire system. The ESP32 receives input signals from the sensors and processes them using embedded algorithms. The core logic includes a tracking algorithm that continuously compares the light intensity values from multiple LDRs. When a significant difference between the readings of the left and right LDRs is detected, the controller



activates the L298N motor driver module, which drives the gear motor to rotate the solar panel in the direction of the brighter LDR. This adjustment continues until the light readings balance, ensuring that the panel always faces the sun for maximum energy capture.

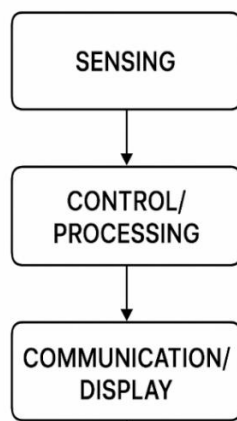


FIGURE I.  
BLOCK DIAGRAM OF SOLAR SYSTEM

The ESP32 also executes the smart metering logic, where it computes the instantaneous power ( $P = V \times I$ ) using the sensed voltage and current data. By integrating power over time, the system determines the cumulative energy generation (in Wh). Simultaneously, the battery management system (BMS) logic monitors the battery voltage levels to ensure safe operation. When the battery voltage drops below a defined Low Voltage Disconnect (LVD) threshold, the ESP32 triggers a relay mechanism to disconnect non-critical loads, thereby protecting the battery from deep discharge. The final component, the Communication and Display Layer, provides both local and remote interfaces for data visualization and control. Locally, the ESP32 updates key parameters such as voltage, current, power, energy, and tracker status on an attached display module, allowing immediate system feedback. For remote monitoring, the ESP32 uses its built-in Wi-Fi capability to transmit all metrics to a cloud-based IoT dashboard using protocols like MQTT or platforms such as Firebase. This enables users to track system performance, energy statistics, and operational status in real time from anywhere.

#### 4.IMPLEMENTATION

To ensure efficient operation, accurate sensing, and reliable power management. Each hardware component plays a crucial role in the proper functioning of the system, with specific electrical considerations taken into account for safety, stability, and precision. At the core of the system lies the ESP32 microcontroller, which serves as the central processing unit. Since the ESP32 operates at a regulated 5V input, a DC-DC buck converter (such as the LM2596) is employed to step down the 12V output from the battery to a stable 5V supply. This regulated voltage powers both the ESP32 and the logic circuitry of the L298N motor driver. The use of a buck converter ensures efficient power conversion with minimal heat dissipation and voltage fluctuations, thereby protecting the microcontroller from overvoltage damage.

To measure electrical parameters, a voltage sensing circuit is integrated using a resistive voltage divider. This circuit scales down the higher panel or battery voltages (typically up to 30V) to the safe 0–3.3V range compatible with the ESP32's analog-to-digital converter (ADC) pins. Proper calibration of this divider network is essential to maintain measurement accuracy and account for any tolerance variations in the resistors used. This allows the system to accurately monitor the voltage levels of both the solar panel and the battery in real time. For current measurement, the system employs a Hall-effect based current sensor (ACS712). The analog output from the ACS712 corresponds to the current passing through the load or panel and is fed into the ESP32's ADC input. Before use, a calibration routine is carried out to determine the zero-current offset voltage and sensor sensitivity (in mV/A), ensuring precise readings. This data is then utilized by the ESP32 to calculate instantaneous power and total energy generation.

The motor control subsystem is implemented using an L298N dual H-bridge motor driver, which enables the ESP32 to drive the 12V DC gear motor responsible for rotating the solar panel. The ESP32 provides two digital control signals to determine the direction of rotation and a PWM (Pulse Width Modulation) signal to regulate the motor speed. The motor's power supply is drawn directly from the 12V battery to ensure adequate torque for panel movement, while the logic



section of the L298N operates at the regulated 5V level from the buck converter. This configuration allows smooth and precise control of the solar tracking mechanism while maintaining system stability.

## 5. EXPERIMENTAL RESULTS AND ANALYSIS

The experimental evaluation of the Sun Solar Tracker System with Smart Meter Integration was conducted to assess its performance in comparison to a conventional fixed solar panel setup. The primary objective was to quantify the improvement in energy generation achieved through automatic sun tracking and to validate the accuracy of the integrated smart metering system. The experimental setup consisted of two identical solar panels: one configured as a fixed panel, positioned at the optimal seasonal tilt angle, and the other equipped with the automatic single-axis solar tracking system. Both panels were exposed to the same environmental conditions over multiple test days to ensure fairness in comparison. The smart meter readings from the ESP32-based monitoring system were cross-verified using a handheld digital multimeter and a clamp meter to ensure measurement reliability.

TABLE II.  
PERFORMANCE COMPARISON

Metric	Fixed Panel (Wh)	Tracked Panel (Wh)	Gain (%)
Daily Energy Yield (Day 1)	200 Wh	245 Wh	22.5%
Daily Energy Yield (Day 2)	210 Wh	255 Wh	21.4%
Average Energy Yield Gain	—	—	≈ 22%

TABLE III.  
SMART METER ACCURACY EVALUATION

Parameter	Actual (Measured by Instruments)	Measured (ESP32 Smart Meter)	Error (%)
Voltage (V)	12.5 V	12.45 V	0.4%
Current (A)	2.0 A	1.96 A	2.0%
Parameter	Actual (Measured by Instruments)	Measured (ESP32 Smart Meter)	Error (%)

Observation: The tracked solar panel consistently outperformed the fixed panel, achieving an average energy gain of approximately 22% due to the automatic tracking mechanism. The smart meter demonstrated high precision, maintaining an error below 5% in both voltage and current measurements. This validates its reliability for real-time energy monitoring and analysis.

## 6. CONCLUSION

In conclusion, this survey paper demonstrates the potential of combining renewable energy generation with intelligent monitoring technology. By integrating an LDR-based dual-axis tracking mechanism with an ESP32-controlled smart metering system, the project achieves efficient solar energy utilization and real-time performance analysis. The system not only enhances power output by ensuring optimal panel alignment with the sun but also enables users to monitor energy production and consumption through both local displays and IoT-based dashboards. This approach highlights the feasibility of a cost-effective, scalable, and energy-efficient solar solution suitable for residential and small-scale



applications. Overall, the project contributes toward promoting smart, sustainable, and automated renewable energy systems, supporting the global transition to cleaner and more intelligent energy infrastructure.

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