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Solar Tracking System and Battery Management

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Abstract

This project focuses on optimizing renewable energy systems by combining a dual-axis solar tracking mechanism with a smart Battery Management System (BMS) to improve solar energy harvesting and storage. The system uses an Arduino Uno microcontroller and Light Dependent Resistors (LDRs) to track the sun's position, enabling the solar panel to adjust its orientation in real-time for optimal sunlight exposure throughout the day. At the same time, the integrated IoT-based BMS monitors key parameters like the state of charge (SOC), voltage, current, and temperature, implementing safety features to prevent overcharging, deep discharging, and overheating. This increases system stability, extends battery life, and guarantees safe and effective energy storage. Comparative analysis of the system shows improved energy capture efficiency, faster response times, and longer battery life. The study demonstrates how combining real-time solar tracking with intelligent energy storage can significantly improve energy utilization, offering a sustainable solution for reducing reliance on traditional energy sources and optimizing renewable energy systems for both residential and industrial use. Through IoT connectivity, the suggested solution facilitates remote monitoring and data visualization, allowing users to assess system performance instantly. For long-term sustainable energy applications, the combination of automated tracking and intelligent battery protection improves overall operating dependability, lowers maintenance needs, and encourages effective use of renewable resources.

Keywords: Solar tracking, battery management system, renewable energy, energy efficiency, sustainable power, IoT

INTRODUCTION

As the world continues to grapple with rising energy demands, environmental challenges, and the depletion of non-renewable resources, renewable energy has become a key part of the solution. Among the various options, solar energy is especially promising, it's clean, abundant, and renewable. But to make the most of it, we need smarter ways to capture and store that energy efficiently. This project explores how we can boost the performance of solar power systems using two main approaches: a biaxial solar tracking mechanism and a smart battery management system (BMS). Typically, solar panels are fixed at a set angle, which means they can't adjust to follow the sun's movement. This reduces how much sunlight they absorb throughout the day. To solve this, we've added a simple solar tracker that rotates the panel from east to west. It's guided by light sensors and controlled using an Arduino Uno, helping the panel stay aligned with the sun for better energy capture [1].

In addition to tracking, we also focused on how the energy is stored. That's where the BMS comes in. It protects the battery by handling the charging

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and discharging processes, keeping the battery healthy over time. It also monitors temperature and prevents overcharging. We've used an ESP32 microcontroller for this, which also allows us to track everything wirelessly in real time [2].

By combining a Solar tracking system and Battery management system, this project delivers a sustainable, automated, and scalable solution for maximizing solar energy utilization. This paper details the design, implementation, working principle, components, advantages, and future potential of the proposed system. The integration of automated monitoring and intelligent control techniques has significantly transformed modern renewable energy systems. In the proposed project, the combination of solar tracking and battery management creates a more adaptive and efficient energy solution capable of responding to varying environmental and operational conditions [10]. Unlike traditional systems that depend heavily on manual adjustment and fixed configurations, this design continuously optimizes energy collection and storage through embedded electronics and sensor-based feedback mechanisms. Such an approach improves the overall effectiveness of solar installations while supporting long term energy sustainability [3].

The solar tracking section of the system operates using light intensity measurements collected from strategically positioned sensors. These sensors detect the direction of maximum sunlight and provide signals to the Arduino Uno controller. Based on the received input, servo motors adjust the orientation of the solar panel to achieve better alignment with solar radiation. This dynamic movement increases the duration of direct sunlight exposure and enhances electrical power generation during different periods of the day. The tracking process is designed to consume minimal energy while delivering improved harvesting performance compared to conventional stationary panels [4].

Energy generated by the photovoltaic panel is transferred to a rechargeable battery system for storage and later utilization. Since battery reliability directly affects the stability of renewable energy applications, the implementation of an intelligent Battery Management System becomes essential. The ESP32 based BMS continuously observes charging conditions and battery health parameters to maintain safe operation [9]. Voltage fluctuations, excessive temperature rise, and abnormal charging states are monitored carefully to prevent battery degradation and operational failure. By maintaining balanced charging and controlled discharge cycles, the system improves battery efficiency and extends service life [5].

An important feature of the proposed model is the integration of wireless communication and real time monitoring capabilities. Through IoT connectivity, users can access system information remotely using smartphones or online dashboards. Parameters such as energy generation, battery condition, charging status, and temperature levels can be observed instantly without requiring direct physical interaction with the setup. This feature enhances user convenience and allows rapid identification of system faults or irregularities [6].

The developed system is suitable for multiple practical applications including household energy systems, agricultural irrigation units, remote communication stations, and smart street lighting. Its compact architecture and low implementation cost make it appropriate for both urban and rural installations. Furthermore, the modular structure of the design allows future expansion with advanced technologies such as artificial intelligence-based prediction models, cloud data storage, and smart grid integration. Therefore, the project represents a reliable and environmentally responsible approach for improving renewable energy utilization and supporting future sustainable power generation requirements [7].

Additionally, the system encourages energy consumption practices by reducing dependence on conventional electricity sources and minimizing unnecessary power losses. The use of affordable hardware components also makes the project accessible for educational institutions and small-scale industries interested in renewable energy experimentation. By combining automation, monitoring,

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protection, and energy optimization within a single framework, the proposed design contributes toward cleaner energy production and smarter resource management for development [8].

LITERATURE SURVEY

A comprehensive literature survey was conducted to understand current technologies and advancements in solar tracking systems and battery management systems. Relevant research papers, patents, technical reports, and online resources were reviewed.

Solar Tracking Systems

Solar tracking systems improve the efficiency of photovoltaic (PV) panels by adjusting their orientation based on the sun's position. There are two primary types:

1. *Single-Axis Trackers*: These rotate along one axis, either horizontal or vertical. They can increase energy output by 20-25% compared to fixed systems.
2. *Dual-Axis Trackers:* These adjust along both horizontal and vertical axes (azimuth and elevation), leading to up to 40% more energy capture. However, they are more complex and costly.

Figure1 illustrates the description of angles – tilt angle, orientation angle. LDR-based trackers are widely used due to their simplicity and affordability. The importance of sensor placement and calibration for optimal performance is emphasized. Challenges like accuracy under cloudy conditions can be addressed with sensor fusion techniques.

Battery Management Systems

A Battery Management System (BMS) is essential for ensuring the safe, reliable, and efficient operation of battery-powered systems

1. *State of Charge (SOC):* Estimating SOC helps prevent overcharging and deep discharging. Kalman filtering and Coulomb counting are common techniques.
2. *Thermal Management*: Overheating can damage batteries. Integrating temperature sensors and cooling strategies helps avoid such risks.
3. *Voltage and Current Monitoring*: Sensors ensure the battery operates within safe voltage and current limits.

Challenges and Future Work

1. *Cost*: High initial cost of dual-axis trackers and advanced BMS.
2. *Weather Sensitivity*: Performance drops in cloudy or rainy conditions.
3. *Maintenance*: Mechanical parts require regular servicing.

Future research is moving toward AI-based tracking systems, predictive analytics, and wireless BMS with cloud integration.

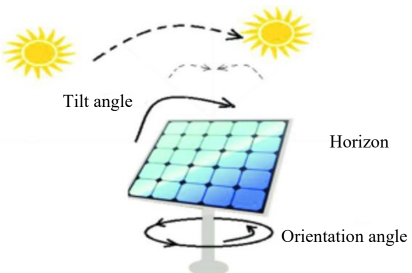

Figure1. Description of angles – tilt angle, orientation angle.

SYSTEM DESIGN AND ARCHITECTURE

The system comprises a solar tracking mechanism and a battery management system. The two systems are synchronized through microcontrollers (Arduino and ESP32), enabling continuous data flow and control.

Software and Logic

Arduino is programmed using C/C++ in the Arduino IDE (Table 1). It continuously reads values from the LDRs, determines which direction has the highest intensity, and sends commands to rotate the servo motor accordingly.

ESP32 is programmed using MicroPython or C/C++ to monitor sensor values and update the battery status. Data can be uploaded to the cloud or displayed via mobile/PC interfaces. Figure 2 illustrates the Dual Axis tracking system.

Hardware Components

Table 1. Components and functions of the proposed solar tracking and battery management system.

S.N	Component	Function
1.	Arduino Uno	Acts as the central control unit for solar tracking
2.	ESP32	Handles battery monitoring, data logging, and wireless communication
3.	LDRs (Light Sensors)	Detect light intensity from multiple directions
4.	Servo Motor	Rotates the panel based on sensor feedback
5.	Voltage and Current Sensors	Monitor battery input/output
6.	Solar Panel	Converts sunlight to electricity
7.	Rechargeable Battery	Stores the converted energy
8.	Buck Converter	Regulates voltage levels
9.	Battery Charging Module	Ensures controlled charging
10.	Chassis and Bearings	Provide mechanical support and movement

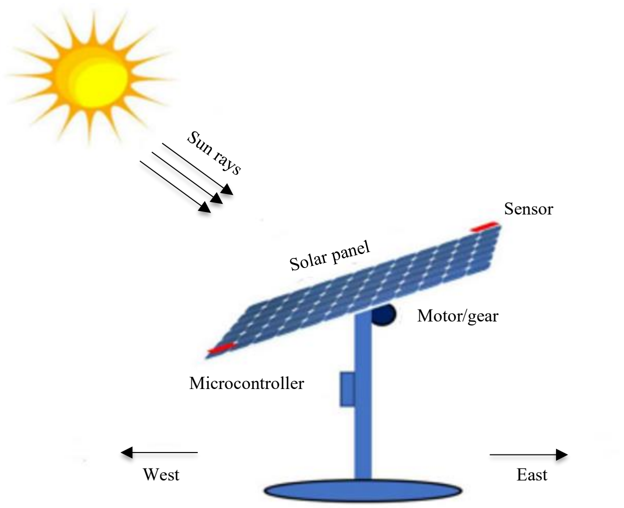

Figure 2. Dual axis tracking system.

SYSTEM WORKING

RESULTS AND DISCUSSIONS

The system was tested under different sunlight conditions and battery loads. It showed a consistent improvement of 30-40% in energy capture compared to a fixed panel. The BMS effectively managed charging cycles and prevented thermal issues. Real-time monitoring allowed timely interventions. The proposed Solar Tracking System and Battery Management model demonstrates significant improvement in renewable energy efficiency through intelligent automation and monitoring. The biaxial solar tracking mechanism increases the exposure of photovoltaic panels to sunlight by continuously adjusting their position according to solar movement. Figure 3 illustrates the flowchart of solar tracking and battery management system. This results in higher energy generation compared to conventional fixed solar panels. The integration of sensors and Arduino based control provides accurate tracking while maintaining low power consumption for system operation. The Battery Management System effectively ensures safe energy storage by monitoring important battery parameters such as voltage, current, and temperature. The inclusion of protection mechanisms against overcharging and overheating improves battery lifespan and operational reliability. Additionally, the use of ESP32 based IoT technology enables real-time wireless monitoring, allowing users to observe system performance remotely. Overall, the project highlights the practical application of embedded systems and renewable technologies in developing sustainable, cost-effective, and energy-efficient power solutions for future smart energy systems. Figure 4 shows the result of battery management realtime analysis.

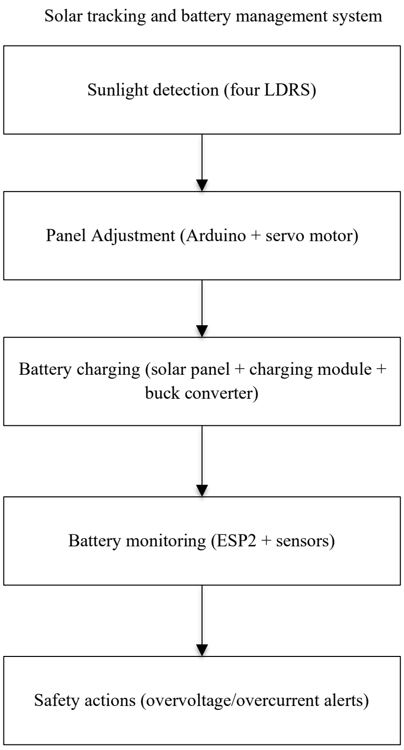

Figure 3. Flowchart of solar tracking and battery management system.

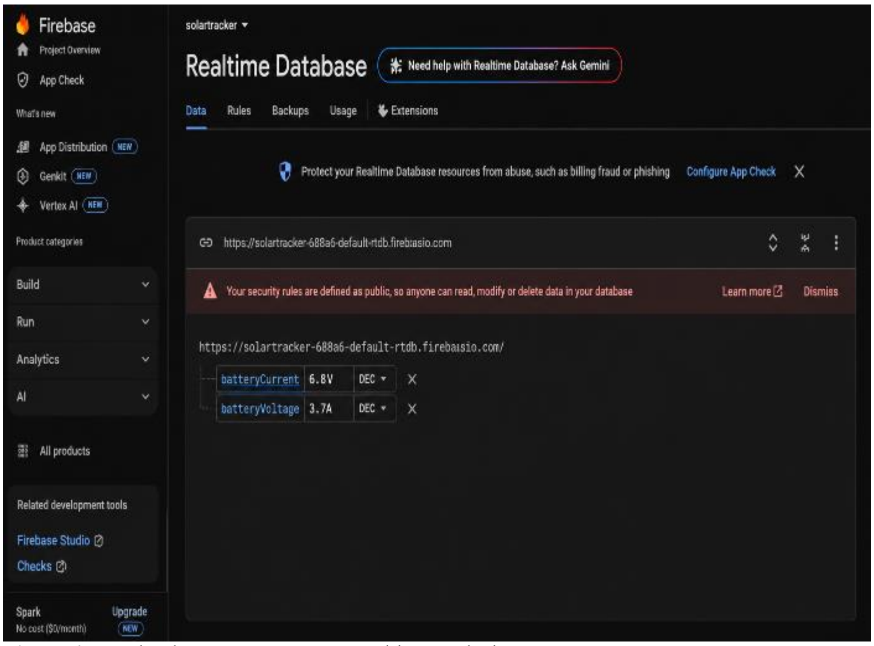

Figure 4. Result – battery management realtime analysis

ADVANTAGES

- Improved energy efficiency (up to 40%).
- Automated panel adjustment.
- Real-time monitoring of battery health.
- Prolonged battery life.
- Scalable and cost-effective.

LIMITATIONS

- Requires periodic maintenance.
- Sensitive to harsh weather.
- Initial installation cost is high.

APPLICATIONS

- Smart homes and buildings.
- Remote agricultural areas.
- Off-grid power systems.
- Electric vehicle charging stations.
- Portable solar generators.

FUTURE SCOPE

- Cloud-based analytics dashboard.
- AI for weather-predictive tracking.
- Integration with smart grids.
- Use of Li-ion and solid-state batteries for better performance.

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CONCLUSION

This project highlights how effective solar tracking can be when combined with a smart battery management system. The setup not only increases the amount of solar energy collected but also ensures that the energy is stored safely and used efficiently. It is affordable to build, easy to scale, and suitable for a range of real world uses. The prototype's positive results suggest strong potential for future improvements and practical deployment in the field. The Solar Tracking System and Battery Management project presents an efficient and sustainable approach for improving renewable energy utilization. By integrating a biaxial solar tracking mechanism with an intelligent Battery Management System, the proposed model successfully enhances both energy harvesting and energy storage performance. The solar tracking system enables the photovoltaic panel to continuously align with the direction of maximum sunlight, increasing solar energy absorption and improving power generation efficiency compared to fixed solar panels. The use of light sensors, Arduino Uno, and automated motor control ensures smooth and accurate panel movement throughout the day. At the same time, the Battery Management System plays a vital role in maintaining battery safety, stability, and long-term performance. Through continuous monitoring of voltage, current, temperature, and charging conditions, the system protects the battery from overcharging, overheating, and deep discharge. The integration of ESP32 based IoT technology also allows real-time wireless monitoring, improving user convenience and operational reliability. Overall, the project demonstrates how automation, embedded systems, and renewable energy technologies can be combined to create an economical and eco-friendly power solution. The developed system reduces energy wastage, supports clean energy generation, and provides a scalable platform for future smart energy applications in residential, agricultural, and industrial sectors.

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