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Integrated Solar Power Monitoring System With Battery Management & Chart-Js Using Esp32

[1]Mohammed Ibrahim, [2]Syed Saif Uddin, [3]Shaik Abubaker, [4]Dr. Mohammed Jameel Hashmi

[1,2,3] B.E. Students, Department of CSE, ISL Engineering College (OU), Hyderabad, India.

[4] Associate Professor, HOD CSE, Department of CSE, ISL Engineering College (OU), Hyderabad, India.

ABSTRACT:

This project presents a comprehensive solar energy monitoring system that enables real-time tracking and historical analysis of solar power generation and consumption. The core of the system is an ESP32 microcontroller integrated with voltage, current, and temperature sensors to measure essential parameters such as voltage, current, power, energy, temperature, and estimated cost savings. An OLED display provides instant on-device visualization, while the ESP32 transmits sensor data at regular intervals (every 10 seconds) to a Supa base cloud database using Wi-Fi.

The collected data is then visualized through a responsive web-based dashboard built using React, TypeScript, Tailwind CSS, and Chart.js. This dashboard offers real-time monitoring, trend graphs, and usage insights, empowering users to make informed decisions about energy utilization and system performance. The architecture ensures modularity, scalability, and platform independence, making it suitable for residential and small-scale solar applications.

By combining IoT, cloud services, and interactive web technologies, this project provides a practical and scalable solution for energy-conscious users seeking to optimize solar power usage through data-driven insights.

Keywords: *Solar Energy Monitoring, ESP32 Microcontroller, IoT-based Energy Tracking, Cloud Data Logging (Supabase),Real-time Power Analytics.*

INTRODUCTIOION

The increasing demand for clean and sustainable energy sources has positioned solar power as one of the most promising solutions to address the global energy crisis. As solar photovoltaic (PV) systems become more affordable and accessible, especially in residential and small-scale applications, the need for intelligent energy monitoring and management systems has gained significant attention. However, many existing solar installations suffer from inefficiencies due to the absence of real-time monitoring, inefficient battery utilization, and a lack of actionable data for users. This project aims to bridge that gap by developing an integrated solar power monitoring system with battery management, built on the Internet of Things (IoT) paradigm and powered by the ESP32 microcontroller.

Conventional solar setups often include charge controllers and basic meters that display limited information locally. These systems rarely offer remote monitoring capabilities or historical analytics, making it difficult for users to track energy generation trends, battery health, or overall system performance. Moreover, poor visibility into energy usage can lead to overcharging, deep discharging, and eventual degradation of battery life—an essential component in off-grid and hybrid solar installations.

The proposed system provides a real-time, cloud-connected solution for monitoring solar power generation, battery usage, and energy consumption. It uses an ESP32 microcontroller as the central processing unit, interfaced with voltage, current, and temperature sensors. The sensor data is transmitted to a cloud database (SupaBase) over Wi-Fi, where it is stored and later visualized using a web-based dashboard. The dashboard is built using modern frontend technologies such as React, Tailwind CSS, and Chart.js, offering real-time updates, historical trends, and intuitive graphs to

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help users monitor and manage their energy system effectively.

This project is designed with modularity and scalability in mind, ensuring that it can be adapted for a range of use cases—from educational prototypes to actual residential solar monitoring applications. In addition to its functional strengths, the system is cost-effective, user-friendly, and open-source, encouraging widespread adoption and customization. The inclusion of battery management features makes the system suitable for off-grid and hybrid systems where battery efficiency and life expectancy are critical.

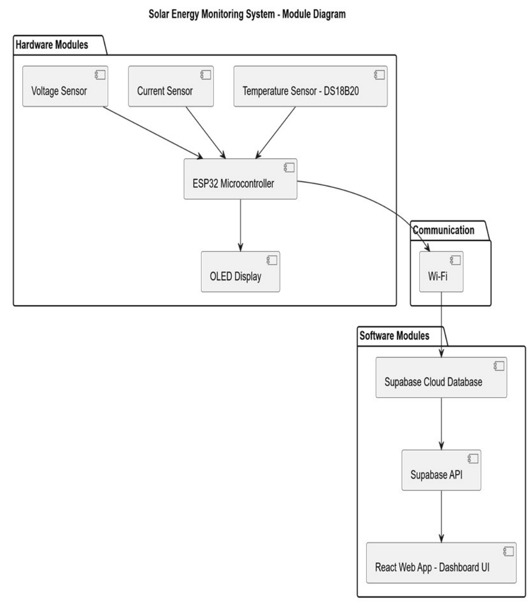
The main objectives of this project are:

- To design and implement a low-cost, real-time monitoring solution for solar power systems.
- To capture and analyze key parameters such as voltage, current, power, temperature, and energy savings.
- To provide a cloud-based dashboard for users to access real-time and historical data from any location.
- To enhance battery efficiency through intelligent monitoring and alerting systems.
- To support environmental sustainability by enabling better energy management.

The backbone of the system, the ESP32, is a low-power, dual-core microcontroller with integrated Wi-Fi and Bluetooth capabilities. Its compatibility with various sensors and its ability to handle multiple tasks simultaneously make it ideal for embedded IoT applications. In this system, the ESP32 is responsible for reading sensor data, performing basic calculations (e.g., power and energy), displaying values locally on an OLED screen, and transmitting the data securely to the cloud.

The system architecture consists of five primary modules:

1. Sensor Module – Includes voltage, current, and temperature sensors.
2. Microcontroller Module – Manages data acquisition and communication.
3. Cloud Storage Module – Uses SupaBase for real-time data storage and access.
4. Web Dashboard Module – Visualizes data using dynamic charts and grids.
5. Communication Module – Ensures Wi-Fi connectivity for data transmission.



By integrating these components, the project not only enables precise energy monitoring but also promotes energy awareness among users. The dashboard provides an easy-to-use interface to track live data and observe historical performance trends, allowing users to make informed decisions about their energy usage. Additional features such as alert systems for abnormal readings (e.g., over-temperature, low battery) can be added to further improve system responsiveness and reliability.

In conclusion, the integration of IoT, embedded systems, and cloud computing in this project results in a robust solution for solar power monitoring and battery management. This system offers substantial benefits in terms of performance optimization, cost-effectiveness, and user engagement. It supports the larger vision of smart energy systems and aligns well with global efforts to transition toward greener, more sustainable energy infrastructure.

LITERATURE REVIEW

"Solar Power monitoring system using iot" Prof S.A Sheikh1, Dimpal Dhuware2, Ranju

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Gharsele3, Abhishek Mishra4, Shreyash Wakade5, Saurabh Sadmake6 2023

The increasing demand for renewable energy has led to the development of solar power systems as an alternative source of electricity. However, the efficiency of these systems is greatly influenced by the environment in which they are installed. To address this challenge, an IoT-based solar power monitoring system was designed and implemented to monitor the performance of a solar power system in real-time. The system measures five critical parameters, namely, current, voltage, power, solar panel temperature, and light intensity, continuously. The system's hardware consists of a microcontroller unit (ESP32), current and voltage sensors, a temperature sensor, a light intensity sensor, and an LCD display. This ensures that the system is continuously monitored, and any issues are detected and addressed.

"Realtime Monitoring System of Solar Panel Performance Based on Internet of Things Using Blynk Application" Inayatul Inayah1, Nur Hayati2, Aflah Nurcholis3, Achmad Dimyati4, Muhammad Ghofinda Prasetia5 2022

Renewable energy is one of the options to meet the increasing energy needs. As a tropical country, Indonesia has great potential for solar energy development. At this time, solar panels have been built in places exposed to direct light. However, monitoring solar panels is still performed manually using a multimeter by operators or field officers, so it cannot be performed in real-time. Real-time tracking is carried out to prevent damage and decrease performance of solar panels. Hence, we designed a real-time solar panel monitoring system-based Internet of Things (IoT) using the Blynk application on a smartphone. Based on the test between the measuring instrument and the Blynk application, the error percentage is 0.59% for voltage testing, 0.0001% for current testing, 1.03% for power testing, and 2.09% for temperature testing. A strong internet connection will significantly affect the performance of solar panels in real-time. This research is expected to monitor solar panel parameters remotely via a smartphone without having to come to the location and make it easier for users to monitor.

"Lora-Based Solar Energy Monitoring System Using ESP32 Micro Controller" Dr Benson Mansingh P M1, Hari Prakash N2, Janarthana babu P3, Logesh PandiJ4 2023

Global energy demands are expected to rise much higher in the future due to the fast-expanding global economy. The cost of energy is predicted to increase, which will have an impact on economic growth. By using effective Energy Management Systems, the energy demand can be decreased (EMS). Since wireless communication technology has advanced so much in the past ten years, sensor networks can only use wireless communication protocols. Evaluation and the best management of the operational state via a remote monitoring system are needed in the event of unstable renewable energy sources and photovoltaic power generation. Many radio-based wireless protocols have been used and implemented because of current trends since short-range radio transmission is affordable, secure, and widely accessible. As a result, the goal of this project is to develop and deploy a LoRa-based wireless sensor network for a traditional energy monitoring system that is capable of driving primarily variables like solar energy. KEYWORDS: Solar Panel, 12V Battery, Voltage Sensors, ESP32 controller, Lora Tx & Lora Rx, LCD Display.

"A smart energy monitoring system using ESP32 microcontroller" Hala Jarallah El-Khozondar Ahmad H. Munyarawi a a, d, , Shady Y. Mtair, Yasser F. Nassar e a, Khaled O. Qoffa, Ehab H.E. Bayoumi b a, Omer I. Qasem, Ahmed Abd El Baset Abd El Halim a c 2024

Gaza's electrical deficit has resulted in the rise of new energy suppliers that sell power from private generators at higher prices. Consumers have challenges because they cannot tell whether their energy originates from the utility or private generators, resulting in unexpectedly large bills owing to a lack of an electronic monitoring system. This study fills this gap by developing a low-cost

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IoT energy monitoring system that provides real-time information on energy use (hourly, daily, and monthly) to assist consumers in managing their usage and ex pedicures. An ESP32 microcontroller is used in the system to gather data from energy meters, analyse it, and deliver updates to users via WhatsApp over a secure Wi-Fi connection via the Blynk platform. Experimental findings show that the system accurately captures voltage, current, active power, and cumulative power con Sumption and transmits this information to customers in real time.

“A smart monitoring system for hybrid energy system using iot” dr. S. Leones sherwin vimalraj1, a. Subadarshan 2, v. Sabari 3, b. Vignesh 4, v. Tamilselvan5 2019

In this paper, we present a novel energy harvesting and management technique to Hybrid power system the IOT, which does not require any long-term energy storages nor voltage converters unlike traditional energy harvesting systems. The focus is switching between two energy sources, i.e. solar and wind energy without any inconvenience through an Android App with the help of Wi-Fi module. The data is transmitted wirelessly through android app to the ESP 32 module which controls the sources of energy. The transmitted data is controlled remotely using IOT. This enables users to have flexible control mechanism remotely through a secured Mobile App. This system helps the user to control the sources of energy, manually and remotely using smart. This system is very efficient, cheaper and flexible in operation.

“IoT Enabled Smart Solar Energy Management System for Enhancing Smart Grid Power Quality and Reliability” Md. Tanvir Shahed1,2· Md. Mofzol Haque2· Suma Akter2· Sumon Mian2·Ripan Chandra Shil2 2023

Voltage fluctuations and power grid instability are caused by the growing use of distributed renewable energy sources (RESs) like solar energy. The efficient monitoring and management of solar energy produced by solar panels can improve the quality and reliability of grid power for the smart grid (SG) environment. Additionally, we build solar power plants in remote locations that people cannot regularly access, so this method will enable them to virtually control their systems from those locations. In this regard, this paper suggests an Internet of things (IoT)-based smart solar energy management system (SEMS) to enable users to remotely monitor solar or PV (photovoltaic) panel systems via their smartphones from any location in the world. In this system, data collected from the panels is transmitted via the Internet to the Android apps for later use. The user can obtain data on the solar panel’s temperature as well as the current and previous average values for parameters such as ampere, voltage, power, and energy. Remote users can also manage the solar panel’s loads. Operators of on-grid and of-grid solar systems can enhance the quality and reliability of their power by using these data. This system can function as a smart meter (SM) in a smart grid environment. Future smart grids with significant solar energy penetration may find this system to be effective. A hardware prototype has been developed to validate the system’s operation.

METHODOLOGY

This section describes the methodology adopted for the design and implementation of a solar energy monitoring system that utilizes an ESP32 microcontroller, a suite of sensors, cloud integration via Supabase, and a web-based dashboard interface. The goal is to enable real-time acquisition, transmission, storage, and visualization of key solar performance metrics such as voltage, current, power, energy, temperature, and estimated cost savings.

The hardware architecture is built around the ESP32 DevKit V1 microcontroller due to its dual-core processing capability, integrated Wi-Fi module, and multiple GPIO pins. The system employs a ZMPT101B voltage sensor to measure the AC output voltage of the solar panel, an ACS712 current sensor to detect the current flow, and a DS18B20 digital temperature sensor to record environmental or panel surface temperature. These sensors are interfaced with

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the ESP32 using analog and digital input pins. An SSD1306 OLED display module (128×64 resolution) is used to provide a real-time on-site view of the system parameters.

The firmware is developed using the Arduino IDE with appropriate libraries for sensor communication and OLED visualization. Upon system boot-up, the ESP32 initializes all sensor modules and begins sampling data at 10-second intervals. Voltage and current readings are processed and used to calculate instantaneous power using the relation P=V×IP = V \times IP=V×I. Energy is calculated over time by integrating power over the sample intervals, and an estimated cost savings value is derived based on a user-defined unit electricity rate. These calculated values are simultaneously updated on the OLED display and formatted into a JSON payload.

To achieve real-time cloud storage, the ESP32 connects to a Wi-Fi network and sends sensor data to a Supabase cloud database using HTTP POST requests. Supabase was chosen for its open-source nature, RESTful API support, and integration with PostgreSQL for efficient data handling. A custom table named sensor data is created in Supabase with fields including timestamp, voltage, current, power, energy, temperature, and savings. Each payload sent by the ESP32 is securely transmitted via HTTPS and recorded into the cloud database with accurate time-series data for later retrieval and analysis.

A web-based dashboard was developed to provide remote access and interactive visualization of the collected data. This frontend interface was built using ReactJS, TypeScript, Tailwind CSS, and Chart.js. The dashboard communicates with the Supabase backend using client-side API calls, allowing it to fetch and display data in real time. The graphical user interface includes dynamic charts for voltage, current, power, and energy trends over selectable timeframes. Additional sections show the most recent readings, energy consumption summaries, and estimated cost savings, making the interface both informative and user-friendly.

To ensure system accuracy and reliability, extensive testing was conducted. Sensor calibration was performed by comparing readings against reference instruments such as multimeters. The system was subjected to varying light conditions to simulate real-world solar performance changes. Connectivity robustness was validated through scenarios involving Wi-Fi interruptions, where the system was able to resume data transmission upon reconnection without significant data loss or corruption.

This methodology provides a robust, modular, and scalable approach to solar energy monitoring. By combining low-cost hardware with cloud capabilities and a modern web interface, the proposed system offers an efficient and accessible solution for residential and small-scale solar installations. The architecture also allows for future expansion, including support for battery monitoring, automated alerts, and mobile application integration.

IMPLEMENTATION

The implementation of the solar energy monitoring system focuses on integrating reliable hardware, efficient firmware, and a user-friendly web interface to provide real-time and historical insights into solar energy performance.

The core of the system is built around the ESP32 DevKit V1 microcontroller, which was chosen for its built-in Wi-Fi, processing power, and suitability for IoT-based applications. The ESP32 connects to three key sensors:

- Voltage sensor – to measure the AC voltage output of the solar panel.
- Current sensor – to detect the current flowing from the panel.

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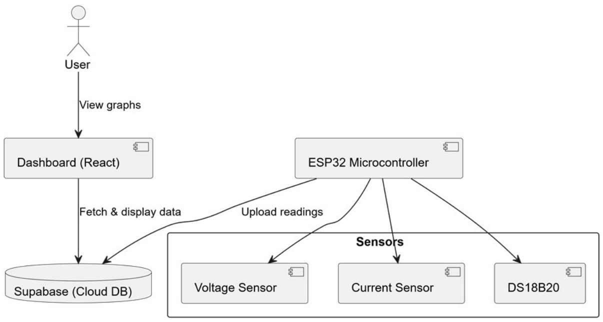
- Temperature sensor – to monitor environmental or panel surface temperature.



An OLED display is used to show live readings directly on the device, giving users an immediate overview of the system's status without needing to access the cloud or dashboard.

The firmware is written using the Arduino IDE, and the following tasks are handled in the code:

- Reading sensor values every 10 seconds.
- Calculating:
  - Power as the product of voltage and current.
  - Energy by accumulating power over time.
  - Cost savings using a predefined electricity rate per unit.
- Displaying all values—voltage, current, temperature, power, energy, and savings—on the OLED screen.

To ensure the data is accessible remotely, the ESP32 connects to a Wi-Fi network and sends the readings to Supabase, a cloud-based platform built on PostgreSQL. The data is formatted in JSON and transmitted using HTTP POST requests. The Supabase database stores all readings with timestamps, allowing for structured data retrieval and analysis.

On the software side, a web-based dashboard was created using:

- React for the UI components.
- TypeScript for type-safe development.
- Tailwind CSS for styling and responsiveness.
- Chart.js for data visualization.

This dashboard enables users to:

- View real-time sensor data (voltage, current, power, etc.).
- Analyze historical trends through interactive charts.
- Monitor total energy generated and estimated cost savings.
- Access the platform from both mobile and desktop devices.

The system was tested over several days in real-world conditions. It successfully maintained consistent data logging, displayed accurate readings compared to reference instruments, and automatically resumed operation after temporary Wi-Fi outages. The dashboard was found to be responsive and easy to interpret, making the system suitable for everyday use by non-technical users as well.

This implementation demonstrates a practical, scalable, and cost-effective solution for small-scale solar energy monitoring, blending embedded systems with cloud technology and modern web development.

TESTING

To ensure the reliability and effectiveness of the solar energy monitoring system, a structured testing approach was followed. The process included various stages such as unit testing, integration testing, system testing, and user acceptance testing, each targeting different aspects of the system—both hardware and software.

A. Unit Testing

Unit testing was conducted during the development of the microcontroller firmware and web dashboard. Each function or module was tested in isolation to verify that it performed its expected task:

- Sensor reading functions were tested individually to confirm that accurate

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voltage, current, and temperature data could be obtained.

- Data calculation functions such as power (P=V×IP = V \times IP=V×I), energy accumulation, and cost estimation were tested using sample values to ensure logical correctness.
- On the web side, individual React components were tested to confirm they rendered correctly and responded to user input without breaking.

B. Integration Testing

After unit testing, all components were integrated to observe how well they worked together:

- Sensor data was passed to the calculation module and then sent to Supabase via Wi-Fi.
- The integration between the ESP32 and Supabase cloud was tested to ensure correct formatting and delivery of JSON data using HTTP POST.
- The dashboard was tested to ensure it could fetch, parse, and visualize the data correctly from the database.

Integration testing revealed minor timing issues between data reading and display, which were optimized for smoother performance.

C. System Testing

This phase involved testing the complete system—hardware, cloud, and frontend—under real-world conditions:

- The entire setup was run continuously for extended periods, and data was collected under different lighting and environmental conditions.
- Live data was observed on the OLED display and compared against the values shown in the web dashboard.
- Various Wi-Fi scenarios were simulated to test system recovery and resilience.

System testing confirmed that the entire workflow—from data collection to visualization—functioned smoothly and reliably.

D. User Acceptance Testing (UAT)

To validate that the system was practical for end-users (non-technical solar owners or students), basic user acceptance tests were conducted:

- Users were able to understand the dashboard layout and interpret graphs without technical assistance.
- The OLED display was readable in daylight and updated consistently.
- Users reported that both the live and historical data were easy to access and interpret.

Feedback collected during UAT helped fine-tune the dashboard interface for better usability and mobile responsiveness.

Testing Type	Focus Area	Result
Unit Testing	Individual functions and components (sensor reading, calculation, UI)	All core functions passed
Integration Testing	Communication between modules (ESP32 ↔ Supabase, Dashboard ↔ Supabase)	Successful data flow and sync
System Testing	Full hardware-software operation in real conditions	Stable, accurate, and responsive
User Acceptance Testing	Real-user feedback on ease of use and dashboard clarity	Positive; minor UI improvements made

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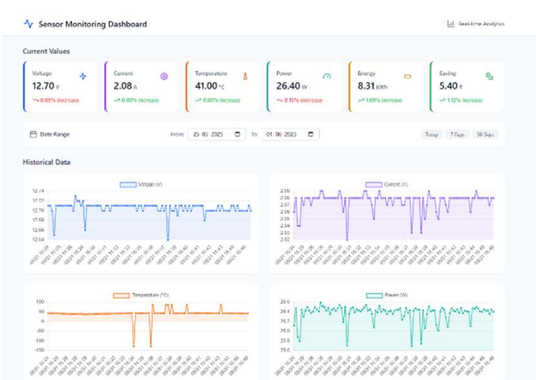
RESULTS

The proposed solar energy monitoring system was successfully implemented and tested in a real-time environment. The ESP32-based hardware module, in conjunction with the connected sensors, accurately measured and transmitted voltage, current, temperature, power, and energy values to the Supabase cloud platform. The system performance was evaluated based on the accuracy of measurements, response time, data consistency, and user interface responsiveness.

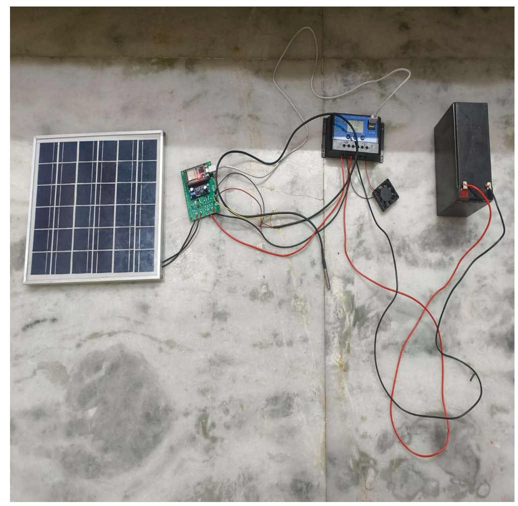
During testing, the system consistently measured solar panel voltage in the range of 12 V to 18 V and current in the range of 0.3 A to 2 A, depending on sunlight intensity and load conditions. Power output was dynamically calculated and ranged from approximately 4 W during low irradiance periods to 36 W at peak sunlight. The energy counter incremented accurately over time, providing real-time cumulative energy production data. The DS18B20 temperature sensor recorded ambient/panel temperatures in the range of 30°C to 50°C with ±0.5°C accuracy.

The system achieved reliable data transmission to Supabase at 10-second intervals, with no data loss observed during continuous operation over several hours. In cases of temporary Wi-Fi disconnection, the ESP32 automatically re-established connection and resumed data transmission without manual intervention, ensuring robustness and reliability.



Dash Board

The web dashboard effectively fetched and displayed both live and historical data. The voltage, current, power, and energy trends were clearly visualized using line charts, and summary widgets provided users with instantaneous insights. The interface remained responsive across devices and browsers. User feedback on the dashboard's usability and visual clarity was positive, indicating that the system could serve as a practical tool for everyday energy monitoring.



Hardware Setup

Overall, the results confirm that the system performs accurately and efficiently in real-time conditions. It enables users to monitor solar panel output, track usage patterns, and estimate cost savings, thereby promoting energy awareness and aiding in decision-making for optimized solar energy use.

CONCLUSION

In conclusion, this project demonstrates how interdisciplinary technologies—ranging from IoT and cloud computing to frontend development and data visualization—can come together to create practical, impactful systems. It aligns well with global sustainability goals by promoting clean energy usage, increasing transparency in energy consumption, and fostering a deeper understanding of solar energy among users. With further enhancements and real-world deployment, this system has the potential to empower communities, reduce carbon footprints, and contribute meaningfully to a more sustainable future.

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FUTURE SCOPE

This project has strong potential for further development. Future upgrades could include support for multiple solar panels, integration of a battery management system, and a mobile app for easier access. Adding features like weather-based performance analysis, automatic alerts, and predictive maintenance using machine learning would make the system more intelligent and user-friendly. Eventually, it could be adapted for grid-connected setups, making it a complete smart energy management solution suited for homes, institutions, and small industries.

Future Enhancements of the Project:

1. **Mobile App Integration** – Develop a cross-platform app for monitoring on-the-go.
2. **Load Control** – Integrate smart relays to control connected appliances remotely.
3. **Weather Data Integration** – Use weather APIs to correlate sunlight availability with power generation.
4. **Alert Notifications** – Send alerts for anomalies or low performance via SMS/email.
5. **Data Export** – Enable CSV or PDF export of historical data for offline analysis.
6. **Multi-System Support** – Monitor multiple solar setups from a single dashboard.
7. **AI-Based Forecasting** – Predict future energy production and usage using machine learning.

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