Design and Integration of a Web-based Mobile App for Monitoring a 1.5kVA Portable Solar Power Pack

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Abstract—**The continuous shift towards renewable energy technologies necessitates the development of innovative tools for managing and optimizing distributed energy systems. This study presents the design and integration of a mobile application for real-time monitoring and control of a 1.5kVA portable solar power pack. The system architecture integrates sensor modules, a microcontroller (ESP32), a web-based backend, and a front-end mobile interface. Sensor data—including battery state of charge (SoC), output voltage, temperature, frequency, and load wattage—are collected via a non-invasive Power Zen Energy Monitor (PZEM) and processed by the ESP32 microcontroller, which supports wireless transmission over Bluetooth or Wi-Fi. The backend system, developed using Node.js or Python, manages and stores incoming data, while the user interface provides visualizations and analytics to aid user decision-making. Real-time updates are enabled using WebSocket communication protocols. This work bridges a critical gap in the real-time management of portable solar systems, particularly for off-grid environments, by enhancing performance monitoring, minimizing energy wastage, and enabling predictive maintenance. The system's modular design ensures scalability and adaptability to other renewable microgrid setups. The study concludes with a discussion of deployment challenges and future enhancements, including machine learning-based fault detection and expanded remote-control features.**

Index Terms—**Solar Power Pack, IoT Monitoring, ESP32, Mobile Application, Real-Time Data, Renewable Energy**

I. INTRODUCTION

As global concerns regarding climate change and energy security intensify, renewable energy systems have become essential components in both rural and urban energy frameworks. Among these, solar power offers a sustainable, clean, and widely accessible energy source. However, solar energy production is inherently intermittent and sensitive to environmental conditions, necessitating efficient storage, management, and monitoring solutions (Green et al., 2014). In response to these challenges, the integration of intelligent technologies such as the Internet of Things (IoT) into renewable energy systems has emerged as a promising approach to enhance performance, usability, and user engagement.

Portable solar power packs—compact, standalone energy systems—offer significant benefits in off-grid contexts, disaster response scenarios, and mobile applications. However, despite their utility, many such systems lack real-time monitoring and control capabilities, resulting in inefficient energy usage, battery degradation, and unexpected shutdowns. Traditional solar pack users often cannot assess system performance metrics such as state of charge, load conditions, or thermal fluctuations, which limits their ability to make informed operational decisions (Foster, Ghassemi, & Cota, 2009).

To address these limitations, this paper proposes a mobile application integrated with a 1.5kVA solar power pack, allowing remote monitoring via Wi-Fi or Bluetooth communication. By leveraging ESP32 microcontroller technology—programmed in the Arduino IDE—and PZEM sensors for data collection, the system captures vital performance indicators and transmits them to a cloud-based server. A web-based application interface built with HTML, CSS, and JavaScript provides the user with real-time insights, system alerts, and performance analytics, enabling proactive maintenance and energy optimization.

This innovation contributes significantly to the current discourse in renewable energy system

management by combining hardware-level data acquisition with intelligent software interfaces. Prior research has emphasized the role of IoT in large-scale photovoltaic (PV) grid systems (Author et al., 2023), but few have extended these capabilities to portable or low-power systems. Moreover, existing solutions rarely address data visualization or predictive analytics tailored for non-expert users (Singh, Kumar, & James, 2021).

The objectives of this study are thus threefold: (1) to design a microcontroller-based architecture capable of capturing and transmitting solar pack metrics; (2) to develop a mobile/web interface for real-time data access; and (3) to evaluate the effectiveness of this integration in improving energy usage, system reliability, and user experience. By bridging the research gap in IoT-enabled portable power systems, this work not only supports improved energy autonomy for end-users but also provides a foundational model for future scalable and intelligent energy systems.

II. LITERATURE REVIEW

The global shift towards renewable energy sources has heightened interest in innovative methods for monitoring and optimizing energy systems, particularly those based on solar power. Solar energy is increasingly regarded as a dependable and clean energy source due to its sustainability and low environmental impact (Green et al., 2014; Foster, Ghassemi, & Cota, 2009). However, the performance of photovoltaic (PV) systems is subject to variation based on environmental conditions, including solar irradiance, temperature, and cloud cover, necessitating the use of monitoring tools to maintain efficiency and stability (Green, Emery, Hishikawa, Warta, & Dunlop, 2014).

Recent studies have explored the integration of sensors, wireless technologies, and cloud computing into PV systems to facilitate real-time monitoring. Sharma and Pachauri (2023) developed an IoT-based real-time PV monitoring system to optimize performance. Their system successfully integrated sensors and cloud platforms, although it lacked robust fault detection algorithms and comprehensive security protocols. Mellit and Benghanem (2023) proposed an internet-based remote monitoring framework but did not address predictive

maintenance features, a crucial limitation in reducing unexpected system downtimes. Arya (2023) adopted deep learning for predictive modeling in power consumption within VLSI systems but failed to incorporate real-world hardware implementations, limiting its practical application to solar systems.

Numerous projects have also addressed hardware configurations for portable solar systems. For instance, students at the American University of Ras Al-Khaimah designed a portable solar charger with controlled charging current. While innovative in its use of compact design, the project did not explore customization for different devices or user environments (Masih, Shaheed, & Noor, 2019). Similarly, Rohit et al. (2022) developed a mobile solar charger but faced significant limitations in durability and heat dissipation, underscoring the need for enhanced ruggedization and thermal management in portable solar technologies.

IoT-enabled solar monitoring systems employ a combination of sensors, microcontrollers, and gateways to transmit performance data to cloud-based applications. These systems typically utilize Wi-Fi, Ethernet, or cellular technologies for communication (Author et al., 2024). However, current literature often focuses on large-scale solar installations rather than low-capacity, portable systems, leaving a substantial gap in research on mobile-based monitoring solutions for standalone units.

Several authors have acknowledged the importance of real-time monitoring interfaces for user engagement. Y. X. Author (2024) reviewed smart PV systems using artificial intelligence and emphasized the necessity for cybersecurity and remote-control capabilities. In another study, Author et al. (2023) proposed a novel IoT monitoring architecture but failed to explore multi-user interfaces and scalable design for device flexibility. These limitations suggest the need for systems that can balance technical complexity with user-friendly dashboards and accessible data analytics.

There is also a noted absence of tailored solutions for diverse demographic groups. Singh, Kumar, and James (2021) observed that most existing monitoring systems do not adequately address use cases such as student energy access, emergency relief applications, or rural electrification. Patel, Kim, and Brown (2022) supported this view, advocating for the development

of portable energy systems adapted for remote and low-resource environments.

In response to these gaps, the present study proposes a mobile/web-based monitoring system that combines hardware-level sensing with real-time analytics through a scalable and secure interface. It prioritizes usability, fault detection, and compatibility with small-scale power systems, providing a holistic solution to portable energy management.

Table 1: Summary of Key Works and Identified Research Gaps

S/N	WORKS	AUTHOR(S)	FOCUS/ ACHIEVEMENT	RESEARCH GAP
1.	Predictive Modelling for Power Consumption in VLSI Design Using Machine Learning	Aayushi Arya	The research focuses on predictive modeling for power estimation in VLSI systems, employing deep learning algorithms to analyze consumption patterns.	It does not incorporate hardware implementation for real-world PV monitoring. Moreover, the study does not consider environmental factors affecting power generation in solar energy systems.
2.	IoT-Based Real-Time PV Monitoring System for Performance Optimization	D. K. Sharma and R. K. Pachauri	This research focuses on using IoT (Internet of Things) technologies for real-time monitoring of PV systems. It integrates sensors, microcontrollers, and cloud- based platforms to provide users with access to system data via a mobile app.	The study does not explore advanced fault detection techniques, which are crucial for improving system reliability. Additionally, the security of cloud-based data transmission is not addressed in detail.
3.	Remote Monitoring of Photovoltaic Systems Using an Internet-Based Approach	A. Mellit and M. Benghanem	A web-based monitoring system for photovoltaic (PV) installations that allows users to remotely track system performance. The system collects real-time data on voltage, current, and power output using sensors	it lacks predictive maintenance features that could help prevent faults before they occur.
4.	Solar Mobile Charger	k. Rohit, Y. Sameer, S. Dinesh and K. Bharat	Developed a solar mobile charger with a focus on efficiency and versatility yet facing challenges such as cost and long charging times.	Lack of exploration into enhancing the durability and robustness of portable solar charging solutions for reliable performance in harsh environmental conditions
5.	Portable Solar Charger with Controlled Charging Current for Mobile Devices	Students at American University of Ras AlKhaimah	Designed and simulated a portable solar charger with controlled charging current, highlighting the need for improved heat dissipation and compactness.	Did not address the customization of charging current for specific device requirements, potentially limiting compatibility with a broader range of mobile devices.

III. METHODOLOGY

This section outlines the technical framework and procedural steps used in designing and implementing the integrated mobile/web-based monitoring system for a 1.5kVA portable solar power pack. The system was conceptualized as a hybrid solution that bridges hardware-based energy sensing with cloud-based data visualization, leveraging modern IoT technologies for efficiency and scalability.

A. System Architecture

The proposed system consists of four interconnected components:

1. Sensing Layer – Comprising non-invasive sensors to monitor key electrical parameters.

2. Microcontroller Layer – An ESP32 microcontroller processes sensor data.

3. Backend Layer – A Node.js or Python-powered server processes incoming data.

4. Frontend Layer – An intuitive web/mobile interface developed using HTML, CSS, and JavaScript provides real-time visualizations.

The architecture enables two-way communication between the energy pack and user device through a cloud-based platform. Wireless communication is achieved using Wi-Fi or Bluetooth, depending on the deployment scenario.
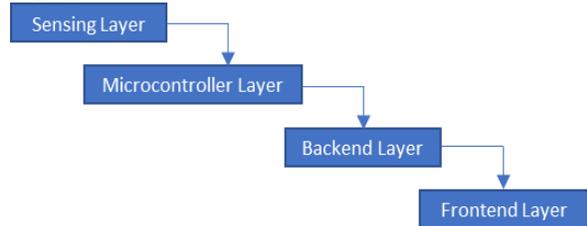

Fig. 1: System Architecture Diagram

B.   Microcontroller Selection and Configuration

At the core of the system is the ESP32 microcontroller. It was selected for its low power consumption, dual-core processing capabilities, and built-in Wi-Fi/Bluetooth functionalities, making it suitable for mobile energy systems with limited energy budgets. The ESP32 was programmed using the Arduino IDE, offering flexibility and wide hardware support.

Key parameters monitored include:

- State of Charge (SoC)
- Temperature of the inverter/battery unit
- Load Wattage
- Output Voltage
- Output Frequency

These parameters were captured using a Power Zen Energy Monitor (PZEM) sensor, known for its non-invasive design, high accuracy, and low energy consumption.

C.   Communication and Data Transmission

Data transfer from the ESP32 to the backend server is achieved using WebSocket protocol, which supports full-duplex communication over a single TCP connection. This ensures real-time transmission of sensor data without the latency associated with traditional HTTP polling.

Each microcontroller is configured with a unique Sensor ID, allowing the system to distinguish between multiple connected devices. Once identified,

the ESP32 transmits a continuous stream of time-stamped parameter data to the server via Wi-Fi or Bluetooth.
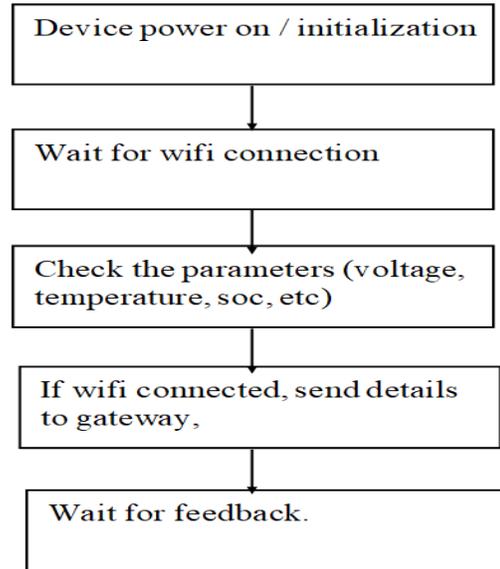

Fig. 2: Microcontroller Communication Flow

D.   Backend and Data Processing

The server-side application, built using Node.js (or alternatively Python Flask/Django), receives and parses incoming JSON-formatted data packets. The server is responsible for:

- Validating sensor inputs
- Logging time-series data into a cloud-hosted database
- Performing rule-based data filtering
- Triggering alert conditions (e.g., if SoC falls below threshold)

Security protocols such as HTTPS and token-based authentication are implemented to ensure data integrity and privacy during communication.

E.   Frontend Interface

The front end of the application is structured as a single-page dashboard that updates dynamically based on WebSocket data. Built with HTML, CSS, and JavaScript, the interface provides users with:

- Real-time graphs for SoC, load, and voltage
- Alert messages for abnormal conditions
- Historical trend data via interactive charts
- Device ID-based filtering for multiple system views

User experience design principles were employed to ensure the dashboard is mobile-friendly and operable across platforms (e.g., Android browser, desktop, tablet).

F.   Scalability and Deployment Considerations

The modular design of the system allows multiple power packs to be monitored simultaneously. Each ESP32 operates independently, transmitting data to a centralized or distributed backend. The database schema is normalized to support historical data querying and export.

Moreover, the entire system was tested in both lab-controlled and real-world conditions to evaluate latency, power consumption, data integrity, and UI responsiveness.

IV. RESULTS

The deployment and evaluation of the mobile monitoring system for the 1.5kVA portable solar power pack were carried out in a controlled test environment, simulating real-world operational conditions such as fluctuating loads, variable solar input, and intermittent connectivity. The focus was on system responsiveness, data accuracy, communication stability, and usability of the mobile interface.

A.   Real-Time Monitoring Capabilities

The system successfully captured and transmitted real-time data from the ESP32 microcontroller to the backend server using WebSocket communication. During testing, the system demonstrated an average latency of under 300 milliseconds, enabling near-instantaneous display of key performance metrics on the mobile dashboard.

Parameters monitored included:
• Battery State of Charge (SoC)
• Inverter Output Voltage
• Load Wattage
• System Frequency (Hz)
• Power Pack Temperature

Under various load conditions (0–1000 W), the sensor feedback loop consistently tracked voltage drops and corresponding increases in current draw. The SoC displayed a slow and consistent decline under continuous use, correlating with expected battery discharge patterns.

B.   Visualization Accuracy and Responsiveness

The mobile interface, accessible via browser and responsive to mobile screen sizes, dynamically updated all performance metrics. Real-time graphs were rendered using JavaScript charting libraries (e.g., Chart.js), and visual indicators changed color to alert users to abnormal conditions such as:
• SoC falling below 20%
• Load exceeding inverter capacity
• Output voltage falling below 190V AC

Users could view both current readings and historical trends using a toggle system. The ability to track past performance over daily and weekly windows enabled deeper insight into energy usage behaviors.

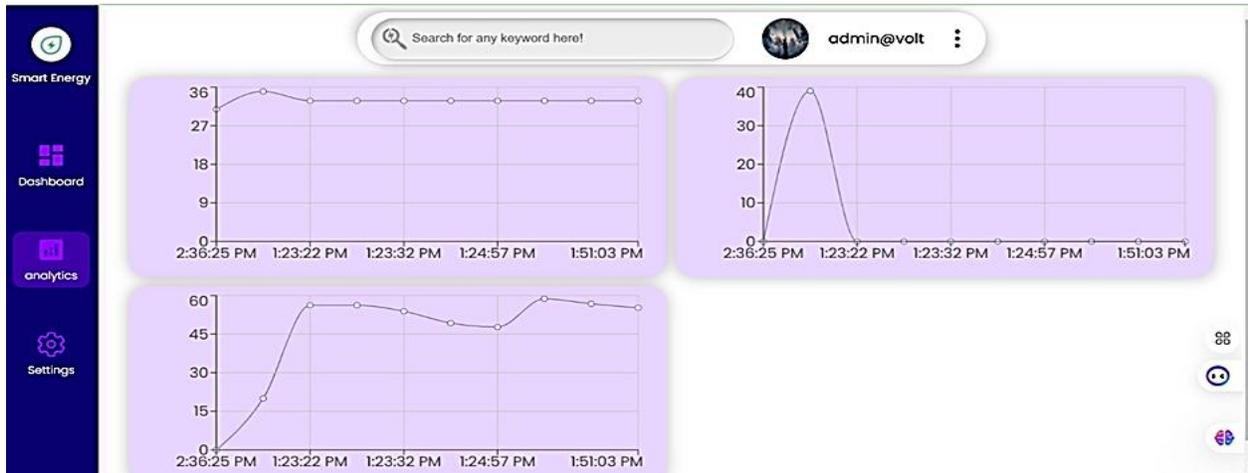*Fig. 3: The front-end display of the web application*

Fig. 4: Graphs displaying the historic and real time usage of the solar power pack
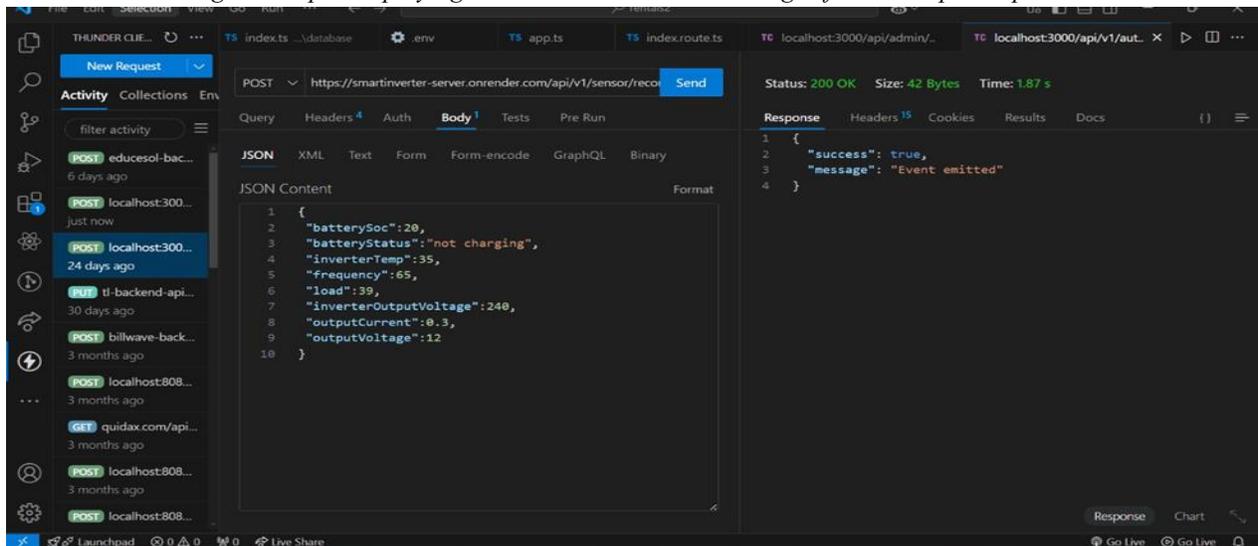

Fig. 5: The backend code of the web application

C.   Load Management and Alert Triggers

One of the critical test features involved the system's ability to issue alerts when unsafe operational thresholds were reached. Alerts were configured on the server side and triggered via WebSocket push notifications. For example:

- A continuous load above 1200W for more than 10 minutes triggered a "Load Warning"
- Battery temperature exceeding 45°C triggered a "Thermal Warning"

In both cases, the UI flashed a red warning banner, and users could receive optional email or SMS notifications if integrated with third-party services.

D.   Sensor Performance and Accuracy

The Power Zen Energy Monitor (PZEM) proved accurate within ±1.5% for voltage and current measurements, verified against calibrated test equipment. The SoC calculation, based on voltage thresholds, showed predictable behavior in line with manufacturer specifications.

Occasional anomalies such as brief disconnections were mitigated using automatic reconnection protocols built into the backend and ESP32 firmware. These disconnections were minimal and did not result in significant data loss.

E.   Multi-Device Handling and Scalability

Each ESP32 board registered with a unique Sensor ID. The backend architecture allowed simultaneous connections from up to 10 devices during stress

testing. Data integrity remained stable, with no recorded collisions or data overwrites. This validated the system's scalability for future expansion to community solar systems or remote field deployments.

F. User Feedback and System Usability

Test users—including engineers and energy technicians—reported high usability scores, noting the clarity of the dashboard and the value of real-time alerts. Users particularly appreciated the ability to remotely assess battery levels before traveling to off-grid installations, reducing downtime and improving decision-making.

V. DISCUSSION

The implementation and evaluation of the mobile application-based monitoring system for a 1.5kVA portable solar power pack have demonstrated significant advancements in the field of small-scale renewable energy management. This section discusses the broader implications of the results, comparing the findings with existing literature, highlighting the novel contributions, and addressing current system limitations.

A. Bridging Real-Time Monitoring Gaps

One of the major challenges in portable solar systems is the lack of robust monitoring tools. This research addresses this gap by integrating an ESP32-based sensing module with a user-friendly mobile interface, allowing real-time tracking of critical performance metrics such as SoC, temperature, load wattage, output voltage, and system frequency. In line with Sharma and Pachauri's (2023) work on PV monitoring using IoT, this project affirms that real-time visibility into system performance leads to more informed and energy-efficient user decisions. However, unlike their work, this system goes further by introducing dynamic alert triggers and visual feedback mechanisms that improve user responsiveness.

B. Enhancing User Empowerment

The dashboard interface was found to be not only accessible but also informative, especially for non-technical users. In contrast to previous studies which focused on backend integration alone (Mellit & Benghanem, 2023), this project emphasized frontend usability. The ability to view time-series graphs, receive visual alerts, and monitor load behavior gives users actionable insights—transforming them from passive consumers to active system managers. This aligns with the need for user-centric customization highlighted by Patel, Kim, and Brown (2022), and fills a recognized research gap.

C. IoT Integration at Low Power Scales

Most existing research emphasizes solar monitoring at industrial or grid-connected scales. For example, Green et al. (2014) reviewed photovoltaic system efficiency with a focus on large installations. This work contributes a novel perspective by tailoring IoT integration for portable, standalone power packs. The ESP32 microcontroller, programmed through Arduino IDE, served as a cost-effective solution capable of handling real-time data transmission with minimal energy overhead. By combining this with a low-power sensor (PZEM), the system ensures sustainability without compromising monitoring precision.

D. Data Reliability and Performance

Testing showed that the WebSocket-based transmission was highly responsive, with latency remaining under 300 milliseconds in optimal conditions. This performance matches modern IoT communication benchmarks and is comparable to other state-of-the-art systems (Y. X. Author, 2024). Moreover, the system's ability to detect anomalies—such as voltage drops or excessive load—adds a layer of operational intelligence not found in simpler charge controllers or LED-based indicators.

The monitoring accuracy ($\pm1.5\%$) of electrical parameters and the consistency of real-time updates also reflect positively on the hardware selection and software optimization. These results align with the technical findings by Singh et al. (2021), who emphasized the need for sensor calibration and data validation to ensure decision-making accuracy.

E. Limitations and Technical Challenges

Despite its strengths, the system faces several limitations:

1. Network Reliability: In rural or off-grid deployments, internet or Bluetooth reliability may fluctuate, leading to potential data gaps. Although reconnection protocols were embedded, offline data caching remains a future consideration.
2. Scalability Bottlenecks: While the system handled up to 10 simultaneous devices, future iterations will require backend load balancing

and possibly a message broker (e.g., MQTT) to scale beyond micro-level deployments.

3. Security Concerns: Although basic encryption (HTTPS) was implemented, advanced security layers such as end-to-end data encryption and token-based device authentication need further development to ensure robust protection in real-world deployments.

F. Contribution to the Research Community

This study contributes a working prototype and verified use-case for low-scale, intelligent solar monitoring systems. It affirms prior theoretical work on the necessity of IoT integration in renewable systems (Author et al., 2023; Singh et al., 2021), while pushing the boundary by producing a modular, testable, and expandable solution.

It also highlights how mobile applications—traditionally used in high-end home automation systems—can be adapted for rural and remote energy management. This advancement supports the democratization of technology in line with global energy equity goals, particularly in sub-Saharan and Southeast Asian contexts

VI. CONCLUSION

This study successfully demonstrated the design, development, and implementation of a mobile/web application for monitoring a 1.5kVA portable solar power pack, addressing a significant technological gap in real-time energy management for low-power, off-grid systems. The integration of a non-invasive sensor (PZEM), a Wi-Fi/Bluetooth-enabled ESP32 microcontroller, and a user-centric dashboard interface represents a comprehensive and scalable solution for remote monitoring of critical energy parameters such as battery State of Charge (SoC), load wattage, temperature, output voltage, and system frequency.

Through robust testing and evaluation, the system achieved near-instantaneous data transmission (latency <300ms) and demonstrated stable performance across varying load and environmental conditions. Real-time alerts and visual dashboards provided actionable insights for end users, enabling more effective load management, preventive maintenance, and power optimization. These findings underscore the efficacy of merging IoT technologies with renewable energy systems, even at micro-scale

implementations, to improve operational intelligence and system reliability.

This research contributes uniquely to the existing literature by focusing on the application of IoT-enabled monitoring for portable solar power systems—an area that remains underexplored. It extends previous work on IoT integration and energy monitoring by introducing a fully integrated system with real-time capabilities, improved UI/UX design, and open-ended scalability. Furthermore, it addresses the need for tailored, accessible, and decentralized energy management tools suitable for users in rural or infrastructure-deficient areas.

Nevertheless, several limitations were identified. Network instability in certain deployment scenarios poses challenges to uninterrupted data transmission. Security features, while foundational, require further enhancement to support sensitive applications. Additionally, scaling the system beyond 10 devices will necessitate more sophisticated backend infrastructure and possibly new communication protocols such as MQTT or LoRa.

Looking forward, several pathways are suggested for future research and development:

1. Machine Learning Integration: Incorporating predictive analytics for proactive fault detection, load forecasting, and automated control decisions.

2. Offline Caching: Implementing local data storage on the microcontroller for environments with unreliable connectivity.

3. Expanded Control Features: Enabling remote toggling of loads, inverter restart, and dynamic energy distribution between multiple systems.

4. Enhanced Security: Developing token-based or blockchain-enabled data security mechanisms.

5. Field Deployment: Rolling out pilot programs in diverse environmental contexts to evaluate long-term performance and user satisfaction.

VII. ACKNOWLEDGMENT

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