Enhancing security in portable solar power supply design for alternative energy applications

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ABSTRACT

Access to reliable electricity remains a challenge in remote and off-grid areas, where conventional power sources are often unreliable or unavailable. This paper presents the design and development of an internet of things (IoT) system for monitoring and securing a portable solar power station tailored for alternative energy applications. The system, which can be recharged using photovoltaic energy sources, employs a coulomb counting method to accurately estimate the battery's state of charge (SoC) and prevent overcharging and overdischarging. The portable power supply provides stable direct current (DC) outputs (5 V, 12 V, 24 V) and an alternating current (AC) output for various remote area applications, including telecommunications and household use. A dual-relay mechanism is used for battery protection: one relay disconnects charging at 100% SoC and reactivates at 70%, while the other disconnects the load at 20% SoC to avoid deep discharge. IoT connectivity enables real-time monitoring and remote control via smartphone. This development promotes efficient energy management, battery longevity, and improved access to sustainable electricity in underserved regions.

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1. INTRODUCTION

Indonesia possesses a total renewable energy generation potential of 3,687 GW, with solar energy accounting for the largest share at 3,295 GW. Indonesia's location on the equator provides it with an average solar energy potential of approximately 4.8 kWh/m² per day [1]. This positions Indonesia as a key player in harnessing sustainable energy resources, making it a highly promising market for renewable energy development. Solar energy has become the energy of the future due to its clean, safe, and sustainable nature compared to other energy sources [2]. Future energy transition policies will position solar power generation to play a significant role in contributing to the national energy mix [3], [4] to achieve the target of 23% renewable energy by 2025 [5]. As of 2023, Indonesia has only achieved approximately half of its 2025 renewable energy target, reaching 12.5%. To bridge this gap, accelerating the adoption of solar energy is crucial. This effort would not only reduce carbon emissions but also increase the electrification ratio and address the electricity crisis in remote, underdeveloped, and frontier regions. Embracing solar energy offers a sustainable solution to drive the nation towards energy resilience and environmental responsibility [6], [7].

Electricity facilities in remote regions often experience frequent outages, limited usage restricted to specific times, and in some areas, there is no electricity network at all. Public infrastructure facilities such as streetlights and telecommunication towers require a continuous power supply to operate effectively [8]. The reliance on diesel generators for electricity not only incurs high fuel costs but also contributes significantly to carbon emissions, highlighting the urgent need for cleaner energy alternatives to reduce costs and minimize environmental impact [9]. The utilization of solar power can serve as a green energy alternative for remote regions; however, battery charging and discharging need to be controlled to optimize performance and extend battery lifespan [10]. Most battery management systems use Arduino [11]. Arduino controllers have some limitations in terms of speed and the number of input/output ports compared to Raspberry Pi and NodeMCU controllers. Therefore, innovative research is needed to develop an IoT-based system for battery security control, DC/AC output power management of solar energy, and its charging stations.

A major challenge in the development of batteries as an energy storage system is their relatively short lifespan. Solar power supplies are generally not equipped with monitoring and security systems for overcharging and overdischarging. Lead-acid batteries are commonly used in electrical equipment today [12]. Given the limited tolerance of batteries to conditions such as overcharging and overheating, the integration of accurate, IoT-based monitoring procedures becomes essential to ensure safe operation and aligns with the development of advanced monitoring systems that provide real-time visualization, data analytics, and continuous surveillance [13]. The main idea behind IoT is to enable physical objects to be integrated into communication systems connected to the internet, allowing us to remotely monitor and control the electrical energy in the power supply and receive real-time results [14].

Despite these developments, several challenges remain unaddressed. First, many portable solar-powered systems still lack integrated, low-cost, and efficient battery management solutions with real-time protection and monitoring. Although previous studies have focused on estimating battery capacity and monitoring solar energy storage [15], [16], few have implemented multi-output DC/AC management tailored for remote applications. Moreover, existing IoT-based systems often prioritize either monitoring or control, but not both in an integrated and scalable form. This research aims to fill this gap by proposing a novel IoT-based portable solar power supply equipped with a dual-purpose system: i) battery protection using coulomb counting for precise state of charge (SoC) estimation and ii) real-time DC/AC load management optimized for various voltage requirements (5 V, 12 V, 24 V, and 220 V AC).

The main contributions of this study are as follows: i) the design and implementation of a portable, NodeMCU ESP32-based solar power system capable of performing accurate SoC estimation through coulomb counting, ii) integration of an intelligent security system to prevent battery damage caused by overcharging and overdischarging, and iii) development of a modular output management system suitable for critical infrastructure in remote regions. These contributions are demonstrated through hardware implementation, system testing, and performance evaluation in real-world scenarios.

Several previous studies related to estimating the remaining battery capacity have been conducted [15], [16]. Accurate prediction of the battery SoC is crucial for safe, efficient, and reliable battery management [17]. Mitigation of predictive power fluctuations in grid-connected photovoltaic (PV) systems with quick response to charging stations has been developed. Several IoT systems based on NodeMCU utilizing the Blynk platform, taking into account the battery capacity of PV storage, have been published [16], [18]. These systems offer an efficient and accessible solution for monitoring and managing solar power storage, enhancing the reliability and performance of renewable energy systems. In addition, the use of the NodeMCU ESP32 offers the advantage of a lower price and reduced power consumption compared to the Raspberry Pi [19].

In this research, an IoT-based system for battery security control and portable solar-powered power supply output management using the NodeMCU ESP32 has been developed. The designed system will accurately predict the remaining battery capacity by utilizing a coulomb counting-based method [16], which also provides security control against overcharging/overdischarging of the battery, and is integrated with a DC/AC output management system that matches the load requirements in remote areas. The research problem has been addressed, focusing on designing and building a portable solar power supply with IoT connectivity that can accurately predict the remaining battery capacity and provide security control against overcharging and overdischarging of the battery. The development of a stable direct current (DC) power output management system for 5 V, 12 V, and 24 V, tailored to meet the needs of telecommunication tower support devices, as well as alternating current (AC) output for other devices in remote areas, has been carried out. This article will present further results of the design.

From a theoretical standpoint, battery management systems (BMS) are critical in renewable energy applications to monitor battery health, ensure safety, and optimize lifespan. SoC estimation, a core function of BMS, can be approached through various methods, including open circuit voltage (OCV) [20], impedance spectroscopy [21], Kalman filtering [22], and coulomb counting [23]. While Kalman filters and data-driven approaches such as neural networks offer high precision, they often demand significant computational resources and complex modeling. Coulomb counting, though simpler, remains widely adopted in embedded systems due to its efficiency and real-time implementation capabilities. This study adopts the coulomb counting method within an IoT-based framework to offer a cost-effective and scalable solution. The system architecture integrates sensing, control logic, wireless communication, and load management into a unified model, reflecting a practical adaptation of BMS theory for decentralized, portable solar power applications.

The remainder of this paper is structured as follows: i) Section 2 describes the overall design methodology and hardware configuration of the proposed system; ii) Section 3 presents the experimental setup and implementation results, provides a critical analysis and discussion of the system performance, and future scalability; iii) Finally, section 4 concludes the findings and outlines possible directions for future research in securing portable renewable energy systems.

2. METHOD

This study employs a design and development approach for an IoT-based battery security monitoring and control of a portable solar power supply management system. In selecting the system architecture, affordability, simplicity, and IoT capability were prioritized to meet the needs of off-grid applications. ESP32 was chosen due to its low power consumption, built-in WiFi, and compatibility with open-source platforms, while the coulomb counting method was selected for its real-time SoC tracking capability with minimal computational overhead. The portable power supply, designed to power both public facilities and residential households, can be recharged at dedicated solar energy charging stations. The algorithm for estimating the battery's SoC is developed based on an enhanced version of the coulomb counting method. State of charge is an important parameter for determining the battery's charge status. SoC represents the percentage of the battery's remaining capacity at a given time. The coulomb counting method is a commonly used approach to determine the SoC of a battery. This method involves reading the current flowing into and out of the battery to calculate the amount of charge entering or leaving the battery. The coulomb counting method is formulated as (1) [24].

$$SoC(t) = SoC(t_0) \pm \frac{\eta}{C_\eta}\int_{t_0}^{t} I\,dt \tag{1}$$

Where:
$SoC(t_0)$ = Initial SoC before the charging/discharging process occurs.
$SoC(t)$ = The current SoC.
η = Battery charging efficiency.
C_η = Maximum battery capacity.
I = Current flowing into or out of the battery.

The system security controls prevent overcharging and overdischarging of the battery. It also includes a DC/AC output management system to ensure compatibility with the specific load requirements. The battery security system will utilize two relays to prevent overcharging and overdischarging. The first relay activates when the SoC reaches a full charge of 100% and deactivates when the SoC decreases to 70%. The second relay activates when the SoC reaches 20%. The monitoring and security system is designed based on IoT, allowing it to be monitored in real-time and remotely via a smartphone. The portable power supply is designed to provide stable DC outputs of 5 V, 12 V, and 24 V, which are suitable for telecommunication tower supporting devices, as well as an AC output to power other devices. The block diagram of the system is shown in Figure 1.

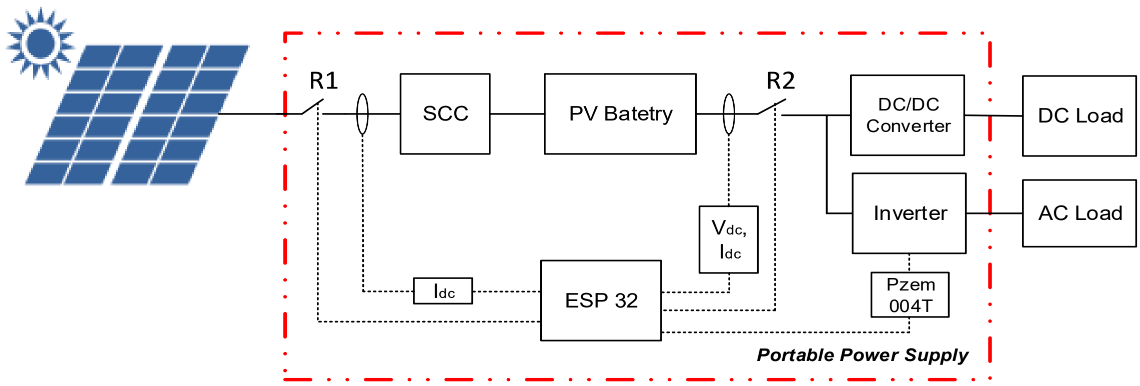


Figure 1. Block diagram of system designed

To estimate the battery's state of charge (SoC), the system employs the coulomb counting method by integrating the net current flow over time. The ESP32 microcontroller reads the charging current (I_{charge}) and discharging current ($I_{discharge}$) through two separate current sensors placed between the photovoltaic panel and the battery, and between the battery and the load, respectively. These current readings are sampled periodically and accumulated to calculate the net charge (Q_net) that has entered or exited the battery. The (2) governs the calculation.

$$SoC(t) = SoC(t_0) + \frac{\eta}{C_\eta} \sum_{i=1}^{n} \left(I_{charge,i} - I_{discharge,i}\right) \cdot \Delta t \quad (2)$$

Where $I_{charge,i}$ and $I_{discharge,i}$ are the instantaneous charging and discharging currents sampled at each time interval Δt. All current measurements are taken by analog sensors and converted via ADC before being processed in the ESP32 firmware.

Figure 2 illustrates the design of the portable solar power supply system with integrated battery security features. During the charging process, the photovoltaic panel is connected to the charge relay, which serves as a switch to control the charging. It is then connected to a solar charge controller that regulates the current flowing from the photovoltaic panel. The system includes a current sensor to collect data on the incoming current, which is then directed to the battery. In the discharging process, the current flows from the battery to a current sensor, which collects data on the outgoing current. The system then connects to the discharge relay, acting as a switch to control the discharging. Afterward, the current is directed to the inverter, which supplies power to the AC load.

Relays 1 and 2 are used to provide battery security by preventing overcharging and overdischarging conditions. When the battery is fully charged, Relay 1 operates to cut off the charging current to the battery solar charge controller (SCC). Meanwhile, when the battery's SoC falls below 20%, Relay 2 is activated to disconnect the load, thereby protecting the battery from deep discharge. These relays play a crucial role in maintaining the battery's health and extending its lifespan by ensuring safe charging and discharging operations. A voltage sensor is installed on the battery to monitor its voltage throughout both the charging and discharging processes. All sensor data is transmitted to the ESP32, which calculates the SoC and sends the data to the Blynk app for real-time monitoring. This system ensures optimal battery management while enabling remote and continuous oversight of the energy supply.

Based on the calculated SoC, the ESP32 implements a control logic for two relays that ensures battery safety. The first relay, known as the charge cut-off relay, is activated (disconnecting the charging path) when the SoC reaches or exceeds 100% to prevent overcharging. This relay is deactivated (reconnecting the charging path) when the SoC drops to 70%, allowing the battery to resume charging. The second relay, referred to as the load disconnect relay, is activated (disconnecting the load) when the SoC falls to 20% to protect the battery from deep discharge. It is deactivated (reconnecting the load) once the SoC rises to 40%, indicating that the battery has sufficient charge to supply power again.

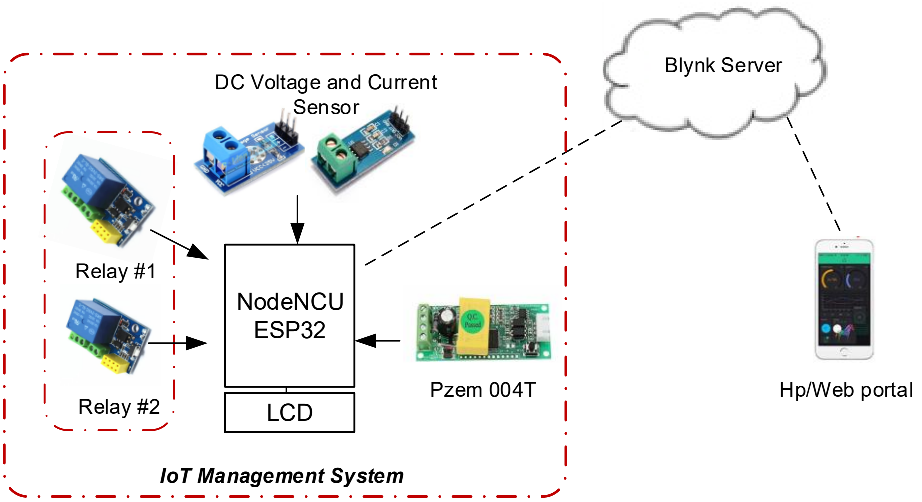


Figure 2. Portable solar power supply components

In addition to current sensing, the system also employs a voltage sensor connected directly to the battery terminals to continuously monitor the battery's voltage level during both charging and discharging processes. This voltage reading provides a secondary reference to validate SoC estimation and contributes to overall system protection and monitoring accuracy. This control logic ensures that the battery operates within a safe SoC range of 20% to 100%, thereby avoiding degradation caused by extreme charging or discharging conditions. Relay control is executed via the digital GPIO pins of the ESP32, and the current SoC and voltage status are continuously updated and transmitted over WiFi to the Blynk application, enabling users to monitor the battery condition in real time remotely.

To ensure reproducibility and clarity, this method integrates both standard and novel components. Standard practices include the use of current sensors (ACS712), voltage dividers, and a solar charge controller for managing energy flow from the PV panel. The novelty of this work lies in the dual-relay cut-off strategy based on SoC thresholds (100%, 70%, and 20%), designed to extend battery lifespan and prevent unsafe charging/discharging. The rationale for using the coulomb counting method is its simplicity and suitability for low-power embedded systems, where more complex SoC estimation algorithms (e.g., Kalman filtering or machine learning) are impractical. The ESP32 microcontroller was selected due to its WiFi connectivity, low cost, and GPIO flexibility, making it ideal for integration with IoT platforms like Blynk. All algorithms, including SoC tracking, threshold-based relay activation, and sensor interfacing, are implemented in C/C++ using the Arduino IDE. The sequence of operations from sensor data acquisition to SoC computation and relay control is executed in loop cycles every one second to ensure real-time system response. With this design, the entire system can be replicated using open-source libraries and standard components.

3. RESULTS AND DISCUSSION

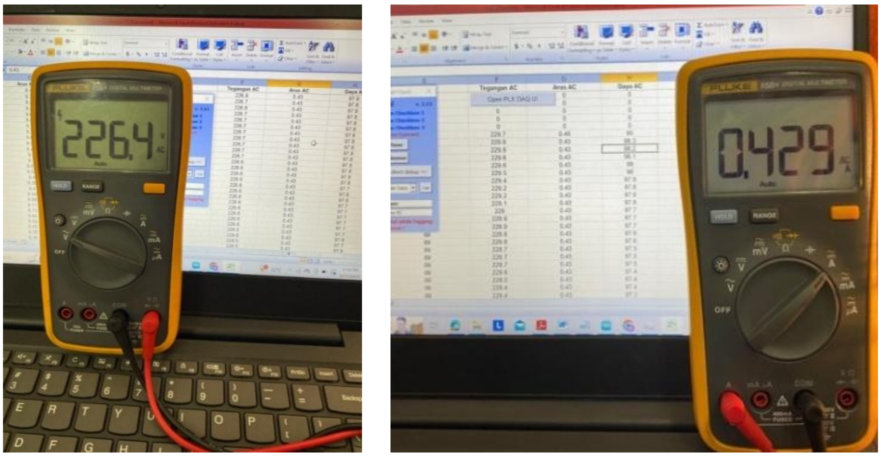
The development of the portable solar power supply was carried out in alignment with the circuit diagrams shown in Figures 1 and 2. All components were assembled according to these schematics, with the resulting setup displayed in Figure 3(a). The main components of the portable solar power supply include a NodeMCU ESP8266, Arduino, current sensor, voltage sensor, PZem sensor, buck/boost converter, and an LCD display. The final build of the portable solar power supply system, featuring integrated battery security functionality, is illustrated in Figure 3(b), highlighting its enhanced capabilities.

Following the design and construction process, the system was tested by calibrating the sensor readings in the output circuit. Calibration and testing were performed iteratively to ensure the device operated effectively and produced accurate measurements during data collection. Once the sensor readings closely matched the reference measurements from standard instruments, a comparison was conducted between the sensor outputs and the results obtained from measuring instruments. Voltage and current testing of the sensors was conducted by uploading a voltage-reading program to the ESP32 microcontroller using the Arduino IDE. A preliminary sensor test was then performed by connecting the sensors during the battery charging process. The sensor readings were monitored using Data Stream Excel and compared with measurements obtained using a multimeter. This rigorous testing process ensured the reliability and precision of the system in real-world applications.

(a) (b)

Figure 3. Portable solar power supply component design: (a) circuits layout without panel box and (b) circuits layout in panel box

The PZEM-004T sensor is utilized to monitor system performance by measuring current, voltage, power, and energy on the AC load when the portable solar power supply is in operation. Therefore, testing the PZEM-004T sensor was conducted to ensure accurate readings during system functionality. The testing of AC voltage and current readings on the PZEM-004T sensor was conducted by uploading a voltage-reading program to the Arduino Mega 2560 microcontroller using the Arduino IDE. Validation was performed by connecting the sensor during the charging or discharging processes of the portable solar power supply. The readings were monitored through PLX-DAQ and compared with measurements obtained from a FLUKE multimeter. The voltage measurements are illustrated in Figure 4(a), while the current readings are shown in Figure 4(b), demonstrating the sensor's precision and reliability.



(a) (b)

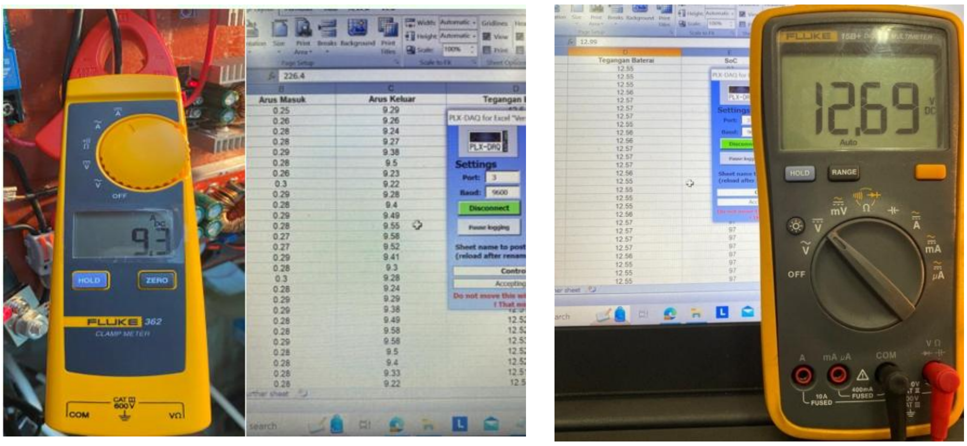
Figure 4. PZem sensor test: (a) voltage measurement and (b) current measurement

Based on the voltage testing data for the PZEM-004T sensor presented in Table 1, the voltage readings from the PZEM-004T sensor closely matched the measurements obtained using a FLUKE multimeter, with an average error rate of 0.05867% for voltage readings and 0.51285% for current readings. These values fall within acceptable tolerance limits, confirming that the PZEM-004T sensor's voltage testing is accurate and the sensor is suitable for implementation in the system.

The ACS712 sensor is used to measure both AC and DC currents. In the system testing, this sensor was employed to measure the DC current flowing from the solar panel to the battery, as well as the DC current flowing from the battery to the load. This ensures effective control of the battery charge to prevent overcapacity or undercapacity during the charging and discharging processes. To validate the accuracy of the sensor readings, testing was conducted by uploading the ACS712 sensor reading program to the Arduino Mega 2560 microcontroller using the Arduino IDE. The test was performed by connecting the sensor's input pin in series within the electrical circuit to detect the flow of DC current, specifically along the current path from the solar panel to the battery. The sensor readings were monitored in real time using PLX-DAQ and systematically compared with reference measurements obtained from a FLUKE multimeter, as illustrated in Figure 5. Figure 5(a) shows that the charging current measured by the sensor closely aligns with the values recorded by the multimeter, indicating the reliability of the current sensing module. Similarly, Figure 5(b) demonstrates a correlation between the voltage sensor readings and the multimeter measurements, further confirming the validity of the voltage sensing circuit.

Table 1. PZem sensor accuracy test

Component	Sensor	Multimeters	Error (%)	Average
PZEM AC volt (PZEM sensor)	226.3	226.2	0.044	0.05867
	226.6	226.4	0.088	
	226.4	226.3	0.044	
PZEM AC current (PZEM sensor)	0.43	0.429	0.2331	
	0.17	0.177	0.03955	0.51285
	0.32	0.316	1.2659	



(a) (b)

Figure 5. Voltage and current sensor test: (a) charging current measurement and (b) voltage measurement

Based on the testing data for the DC voltage and current sensors presented in Table 2, the voltage and current readings from the DC sensors closely matched the measurements from the FLUKE multimeter, with an average error rate of 0.83467% for voltage and 0.48067% for current. These results indicate that the DC sensor readings are within the acceptable error tolerance limits, confirming that the DC sensors are reliable and suitable for implementation in the system.

The data collection for the battery management system during the charging condition includes the charging current, load current, and the battery's SoC simultaneously. As a result, the battery capacity readings are obtained according to the battery management system method implemented, which uses coulomb counting, as shown in Figure 6. From Figure 6, it can be observed that when the charging current is greater than the load current, the battery's SoC curve continues to rise. This is because, essentially, the accumulation of current is charging the battery.

Table 2. Voltage and current accuracy test

Component	Sensor	Multimeters	Error (%)	Average
VDC battery (voltage sensor)	12.64	12.71	0.551	0.83467
	12.54	12.69	1.182	
	12.87	12.97	0.771	
I DC PV (ACS712 sensor)	2.91	2.90	0.345	
	3.43	3.40	0.882	0.48067
	9.32	9.30	0.215	

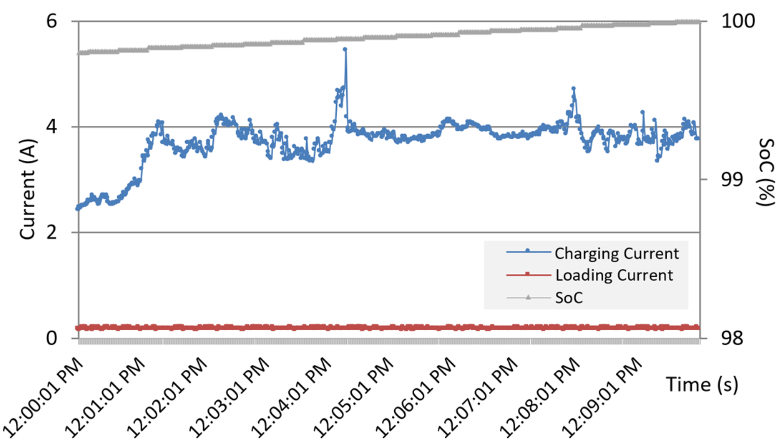


Figure 6. SoC battery during charging process

The data collection for the battery management system during the discharging process includes the load current, charging current, and the battery's SoC simultaneously. As a result, the battery capacity readings are obtained according to the battery management system method implemented, which uses coulomb counting, as shown in Figure 7. From Figure 7, it can be observed that during the discharging process, the battery's SoC curve decreases more significantly compared to the charging process. This is because the current is being used to power the load, leading to a reduction in the battery's capacity. Additionally, the battery's SoC during the loading process is higher than in the charging process, as the battery's energy is consumed more rapidly when discharging.

The discharge process in Table 3 shows that the SoC status has reached the specified maximum voltage of 14 V and SoC 100%. When the battery reaches maximum charge, cut off 1 will be active (ON) and the battery is in discharging status. The installed load can use the energy stored in the battery, so the SoC will decrease. When the estimated SoC reaches 70%, cut off 1 will turn off (OFF). Because energy is used when the estimated SoC reaches 70%, the battery status will change to re-charging, and energy will continue to flow to the load. This relay allows the load to still be able to use the remaining energy in the battery carefully because the battery is almost empty. The process continues until the sun sets the remaining energy will continue to flow to the load. When the SoC drops to 20%, the cut off relay 2 will activate (ON) and cut off power to the load, protecting the battery from over-discharging.

The battery will begin recharging as sunlight becomes available, starting from a remaining SoC of 20%. During this phase, the battery enters the recharging state. Once the SoC reaches 40%, cut off relay 2, which was previously activated, will be deactivated, allowing the load to reconnect and resume drawing energy from the battery, as illustrated in Table 4. This automation will take place continuously, and the incoming and outgoing flow conditions can be monitored using IoT Blynk.

Monitoring solar power supplies is carried out using IoT with the Blynk user interface. The Blynk application is not related to any chips or components, but the microcontroller board used must have WiFi access to be able to communicate with Blynk. Blynk's primary goal is to make it easy to monitor and control devices from the web and mobile. Blynk programming begins by entering the auth token, SSID, and WiFi password. The Blynk dashboard will display all the added widgets. By utilizing the widget features available on Blynk, the monitoring display can interact with the controlled hardware. Each widget can be configured by setting specific parameters. The interface will display the parameter values of incoming current, outgoing current, voltage, SoC, and relay status. The widget used is a gauge to display SoC a value display to display current and voltage values.

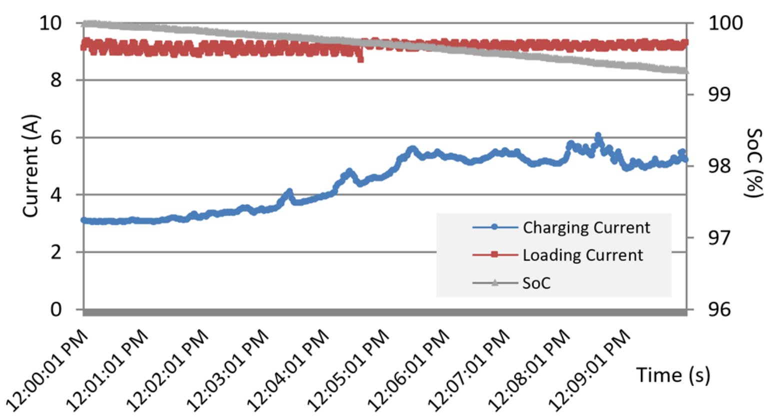


Figure 7. SoC battery during loading higher than charging process

Table 3. Discharging process

No	(V battery)	SoC (%)	Cut off 1	Cut off 2	Charging/discharging	Load
1	14	100.00	ON	OFF	Discharging	Loading
2	13.5	83.33	ON	OFF	Discharging	Loading
3	13.1	70.00	OFF	OFF	Recharging	Loading
4	13	66.67	OFF	OFF	Charging	Loading
5	12.5	50.00	OFF	OFF	Charging	Loading
6	12.2	40.00	OFF	OFF	Charging	Loading
7	12	33.33	OFF	OFF	Charging	Loading
8	11.6	20.00	OFF	ON	Charging	Disconnect
9	11.1	3.33	-	-	-	-
10	11	0	-	-	-	-

Table 4. Charging process

No	(V battery)	SoC (%)	Cut off 1	Cut off 2	Charging/discharging	Load
1	11	0	-	-	-	-
2	11.1	3.33	-	-	-	-
3	11.6	20.00	OFF	ON	Recharging	Disconnect
4	12	33.33	OFF	ON	Charging	Disconnect
5	12.2	40.00	OFF	OFF	Charging	Reconnect loading
6	12.5	50.00	OFF	OFF	Charging	Loading
7	13	66.67	OFF	OFF	Charging	Loading
8	13.1	70.00	OFF	OFF	Charging	Loading
9	13.5	83.33	ON	OFF	Discharging	Loading
10	14	100.00	ON	OFF	Discharging	Loading

The design and implementation of the portable solar power supply with integrated battery management and security features have been successfully demonstrated. Through rigorous testing, including calibration and validation of sensor readings, it was confirmed that both the PZEM-004T and ACS712 sensors deliver accurate measurements of voltage, current, and power under various operating conditions. The high accuracy of the sensors used, particularly the PZEM-004T and ACS712, plays a critical role in ensuring the reliability of the coulomb counting SoC estimation. Inaccurate current or voltage readings could result in faulty SoC calculations, which in turn could lead to premature battery degradation or system shutdown. The sensor accuracy within acceptable error margins demonstrates that the proposed system has met the necessary threshold for dependable off-grid applications, where maintenance and calibration opportunities are minimal.

The coulomb counting method used to estimate the battery's SoC provides reliable data throughout both the charging and discharging processes. The results show that the system operates efficiently, with sensor readings closely matching those from standard measurement tools, ensuring that the portable solar power supply can be safely and effectively used in real-world applications. The integration of IoT capabilities for real-time monitoring further enhances the system's functionality, providing a robust solution for managing solar energy in an automated and secure manner.

While the system has demonstrated reliable SoC estimation through the coulomb counting method, it is important to acknowledge more advanced approaches in recent literature. Kalman filtering techniques are widely used for SoC prediction due to their ability to reduce noise and improve estimation accuracy based on mathematical battery models. Likewise, machine learning methods, such as neural networks or LSTM models have shown potential in learning battery behavior from historical data for more adaptive SoC estimation. However, these methods typically require higher computational resources, complex model training, and are less suitable for low-power embedded systems in rural or off-grid applications. Therefore, this study adopts the coulomb counting approach due to its simplicity, ease of implementation, and compatibility with the ESP32 platform. When supported by reliable current and voltage sensing, this method provides sufficient accuracy for practical field applications, making it a viable solution for decentralized energy systems.

Compared to previous implementations using Kalman filter [25] or machine learning-based [26] SoC prediction, the coulomb counting method offers a significantly simpler and resource-efficient alternative. While those advanced approaches may achieve higher precision under laboratory conditions, they often require sophisticated battery models, extensive datasets, and higher computational power not suitable for low-cost microcontrollers like the ESP32. In contrast, the method presented in this work prioritizes affordability, modularity, and ease of deployment in rural or off-grid areas, which aligns more closely with the operational constraints and scalability goals of decentralized renewable energy systems.

In addition to the technical validation and method selection, it is important to consider the system's capacity for scalability and energy independence. The proposed system demonstrates key features of energy autonomy, particularly through its ability to operate independently in off-grid areas using solar energy. With sufficient battery capacity and proper SoC-based control, the system can sustain basic loads even during nighttime, assuming the energy demand and battery storage are properly matched. While the current implementation is optimized for small-scale applications, the design can be modularly expanded by adding more PV panels, battery banks, and output channels. The use of ESP32 allows flexibility for monitoring multiple inputs and managing additional relays or load priorities. In future developments, integrating power balancing strategies such as load prioritization, DC bus regulation, or time-based energy scheduling can enhance system performance under variable generation and consumption conditions. This would further strengthen the system's scalability and suitability for broader rural electrification programs. The implementation of such a system can has a tangible impact on Indonesia's broader electrification agenda, especially in supporting the 23% renewable energy target by 2025. By enabling localized, IoT-monitored solar energy systems with integrated battery protection, this solution directly addresses the electricity access gap in frontier, remote, and underdeveloped areas. Moreover, the modular nature of the design ensures compatibility with government or private-led initiatives to deploy microgrids or portable solar kits, offering a cost-effective tool for energy democratization and sustainability.

Furthermore, from an economic and lifecycle perspective, the proposed system was developed using low-cost components, such as the ESP32 microcontroller, PZEM-004T, and ACS712 sensors, which offer an effective balance between performance and affordability. This makes the system accessible for low-income and rural communities. The modular design minimizes maintenance complexity and facilitates easy part replacement, reducing long-term operational costs. In terms of lifecycle, the system's reliance on lead-acid batteries, while not the most advanced, ensures widespread availability and straightforward recycling processes. The inclusion of a battery protection mechanism through accurate SoC control also extends battery lifespan, contributing to a lower total cost of ownership. Future research may further optimize the economic viability by integrating lifecycle cost modeling and assessing trade-offs between battery types or alternative energy storage options.

4. CONCLUSION

This study successfully designed and implemented a portable solar power supply system equipped with battery management and security features, validated through testing that showed high accuracy from the PZEM-004T and ACS712 sensors, with average voltage and current error rates of 0.83467% and 0.48067% respectively, and 0.51285% for ACS712 current readings, all within acceptable limits. The SoC estimation using the coulomb counting method effectively tracked battery capacity, where the SoC increased during charging and decreased during discharging, aligning with expected behavior. A dual-relay protection mechanism was implemented: Relay 1 activated at 100% SoC and turned off at 70%, while Relay 2 cut off the load at 20% to prevent overdischarge. These controls operated in real-time through the Blynk-based IoT interface, enabling remote monitoring and safe energy management. The system delivered stable 5 V, 12 V, and 24 V DC outputs and AC power, suitable for telecommunications and other remote-area applications. The integration of accurate sensors, simple yet effective SoC estimation, and real-time IoT monitoring makes the system practical for off-grid use. Furthermore, its modular design allows future scalability, and its simplicity offers advantages over more complex prediction methods such as Kalman filters or machine learning, making it a viable solution to support decentralized renewable energy deployment and national electrification targets.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [S], upon reasonable request.

REFERENCES

[1] K. Kunaifi, A. Reinders, D. Kaharudin, A. Harmanto, and K. Mudiarto, "A comparative performance analysis of a 1 MW CIS PV system and a 5 kW Crystalline-Si PV system under the tropical climate of Indonesia," *International Journal of Technology*, vol. 10, no. 6, p. 1082, Nov. 2019, doi: 10.14716/ijtech.v10i6.3612.

[2] Z. Abdmouleh, R. A. M. Alammari, and A. Gastli, "Review of policies encouraging renewable energy integration & best practices," *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 249–262, May 2015, doi: 10.1016/j.rser.2015.01.035.

[3] National Energy Council, "Indonesia energy outlook 2019," 2019. [Online]. Available: https://www.esdm.go.id/assets/media/content/content-indonesia-energy-outlook-2019-english-version.pdf.

[4] L. Sani, D. Khatiwada, F. Harahap, and S. Silveira, "Decarbonization pathways for the power sector in Sumatra, Indonesia," *Renewable and Sustainable Energy Reviews*, vol. 150, 2021, doi: 10.1016/j.rser.2021.111507.

[5] President of the Republic of Indonesia, *Government Regulation of the Republic of Indonesia No. 79 of 2014, Concerning: National Energy Policy (in Bahasa: Peraturan Pemerintah Republik Indonesia No. 79 Tahun 2014, Tentang: Kebijakan Energi Nasional)*. Indonesia, 2014. [Online]. Available: https://jdih.esdm.go.id/common/dokumen-external/PP No. 79 Thn 2014.pdf.

[6] M. H. Kabir, S. M. S. Newaz, T. Kabir, and A. S. Howlader, "Integrating solar power with existing grids: strategies, technologies, and challenges & review," *International Journal of Science and Engineering*, vol. 1, no. 2, pp. 48–62, May 2024, doi: 10.62304/ijse.v1i2.142.

[7] S. Muchande, S. Thale, and R. Wandhare, "Integrated solar PV-battery and micro-hydro based low-voltage autonomous DC microgrid for rural electrification," in *2020 47th IEEE Photovoltaic Specialists Conference (PVSC)*, Jun. 2020, pp. 2612–2618, doi: 10.1109/PVSC45281.2020.9300876.

[8] A. Abdulmula *et al.*, "Micropower system optimization for the telecommunication towers based on various renewable energy sources," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 12, no. 2, pp. 1069–1076, Apr. 2022, doi: 10.11591/ijece.v12i2.pp1069-1076.

[9] N. K. Bahgaat, N. A. Salam, M. M. Roshdy, and S. A. E. Sakr, "Design of solar system for LTE networks," *International Journal of Environmental Sustainability and Green Technologies*, vol. 11, no. 2, pp. 1–15, Jul. 2020, doi: 10.4018/IJESGT.2020070101.

[10] Dwipayana, I. Garniwa, and H. Herdiansyah, "CO2 emission reduction from solar power plant in rural area (study of solar power plant in Sukaraksa Village, Tanjung Sari Sub-District, Bogor Regency)," *E3S Web of Conferences*, vol. 65, p. 05017, Nov. 2018, doi: 10.1051/e3sconf/20186505017.

[11] R. N. Hasanah, S. Soeprapto, and H. P. Adi, "Arduino-based automatic transfer switch for domestic emergency power generator-set," in *2018 2nd IEEE Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC)*, 2018, pp. 742–746, doi: 10.1109/IMCEC.2018.8469629.

[12] K. Dhanabalan, P. T. Thong, M. Prakash, and H. Y. Jung, "Graphitic carbon nitride/carbon coating on negative plate extends lead-acid batteries cycle life," *Journal of Power Sources*, vol. 641, p. 236861, Jun. 2025, doi: 10.1016/j.jpowsour.2025.236861.

[13] I. González, A. J. Calderón, and F. J. Folgado, "IoT real time system for monitoring lithium-ion battery long-term operation in microgrids," *Journal of Energy Storage*, vol. 51, p. 104596, 2022, doi: 10.1016/j.est.2022.104596.

[14] T. S. Muratkar, A. Bhurane, and A. Kothari, "Battery-less internet of things–a survey," *Computer Networks*, vol. 180, p. 107385, Oct. 2020, doi: 10.1016/j.comnet.2020.107385.

[15] X. Cheng, X. Liu, X. Li, and Q. Yu, "An intelligent fusion estimation method for state of charge estimation of lithium-ion batteries," *Energy*, vol. 286, p. 129462, Jan. 2024, doi: 10.1016/j.energy.2023.129462.

[16] C. Wang, X. Zhang, X. Yun, and X. Fan, "A novel hybrid machine learning coulomb counting technique for state of charge estimation of lithium-ion batteries," *Journal of Energy Storage*, vol. 63, p. 107081, Jul. 2023, doi: 10.1016/j.est.2023.107081.

[17] B. Balasingam and K. Pattipati, "Elements of a robust battery-management system: from fast characterization to universality and more," *IEEE Electrification Magazine*, vol. 6, no. 3, pp. 34–37, 2018, doi: 10.1109/MELE.2018.2849918.

[18] E. Buchicchio, A. De Angelis, F. Santoni, P. Carbone, F. Bianconi, and F. Smeraldi, "Battery SOC estimation from EIS data based on machine learning and equivalent circuit model," *Energy*, vol. 283, p. 128461, Nov. 2023, doi: 10.1016/j.energy.2023.128461.

[19] Syafii, Krismadinata, Muladi, T. K. Agung, and D. A. Sandri, "Simple photovoltaic electric vehicles charging management system considering sun availability time," *Journal of Sustainable Development of Energy, Water and Environment Systems*, vol. 12, no. 1, 2024, doi: 10.13044/J.SDEWES.D11.0476.

[20] U. N. Jibhkate and U. B. Mujumdar, "Development of low complexity open circuit voltage model for state of charge estimation with novel curve modification technique," *Electrochimica Acta*, vol. 429, p. 140944, Oct. 2022, doi: 10.1016/j.electacta.2022.140944.

[21] E. Buchicchio, A. De Angelis, F. Santoni, P. Carbone, F. Bianconi, and F. Smeraldi, "Dataset on broadband electrochemical impedance spectroscopy of lithium-ion batteries for different values of the state-of-charge," *Data in Brief*, vol. 45, p. 108589, Dec. 2022, doi: 10.1016/j.dib.2022.108589.

[22] W. Kai, F. Xiao, P. Jinbo, R. Jun, D. Chongxiong, and L. Liwei, "State of charge (SOC) estimation of lithium-ion battery based on adaptive square root unscented Kalman filter," *International Journal of Electrochemical Science*, vol. 15, no. 9, pp. 9499–9516, Sep. 2020, doi: 10.20964/2020.09.84.

[23] H. Huang *et al.*, "A comprehensively optimized lithium-ion battery state-of-health estimator based on local coulomb counting curve," *Applied Energy*, vol. 322, p. 119469, Sep. 2022, doi: 10.1016/j.apenergy.2022.119469.

[24] Y. Wu, H. Zhao, Y. Wang, R. Li, and Y. Zhou, "Research on life cycle SOC estimation method of lithium-ion battery oriented to decoupling temperature," *Energy Reports*, vol. 8, pp. 4182–4195, Nov. 2022, doi: 10.1016/j.egyr.2022.03.036.

[25] J. Luo, J. Peng, and H. He, "Lithium-ion battery SOC estimation study based on Cubature Kalman filter," *Energy Procedia*, vol. 158, pp. 3421–3426, Feb. 2019, doi: 10.1016/j.egypro.2019.01.933.

[26] O. Ali *et al.*, "On-line WSN SoC estimation using Gaussian process regression: an adaptive machine learning approach," *Alexandria Engineering Journal*, vol. 61, no. 12, pp. 9831–9848, Dec. 2022, doi: 10.1016/j.aej.2022.02.067.

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