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Original Research Article

Enhancing Electric Vehicle Charging Stations through Internet of Things Technology for Optimizing Photovoltaic and Battery Storage Integration

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ABSTRACT

This study explores the integration of electric vehicles with photovoltaic systems in a building-level energy management framework, utilizing an Internet of Things-based system for real-time monitoring and optimization. The proposed system is implemented using a Raspberry Pi as the primary controller, interfacing with various sensors to track voltage, current, power, and energy consumption. A web-based platform is developed to enable seamless remote monitoring and control, ensuring efficient switching between solar power and the utility grid. The battery management system, incorporated within the framework, enhances operational reliability by optimizing charging and discharging cycles. Experimental validation demonstrates that the system effectively maintains voltage stability during source transitions while maximizing the utilization of solar energy. A case study in Indonesia further confirms the feasibility of this approach in promoting energy efficiency and sustainable charging infrastructure, contributing to broader clean energy adoption and reduced dependency on fossil fuels.

KEYWORDS

Electric Vehicles, Photovoltaic Systems, Internet of Things, Battery Management System, Energy Management, Voltage Stability.

INTRODUCTION

The integration of electric vehicles (EVs) with rooftop photovoltaic (PV) systems offers significant potential for localized energy optimization and advancing the United Nations Sustainable Development Goals (SDGs), particularly in clean energy adoption and climate action. While prior studies have demonstrated the environmental benefits of EVs and PV systems, such as reducing greenhouse gas emissions and dependence on fossil fuels, the integration of these technologies at the building level remains underexplored. Specifically, challenges in real-time energy management, effective switching between solar and grid power,

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and battery performance optimization have been identified as critical gaps in existing research [1] [2]. Furthermore, the concept of self-consumption has gained prominence as a way to align with SDG 12 (Responsible Consumption and Production), emphasizing the need to utilize renewable energy at its source and reduce reliance on centralized grids [3]. Addressing these challenges, this study focuses on developing a building-level energy management system utilizing Internet of Things (IoT) based monitoring and control technologies, emphasizing behind-the-meter integration. By bridging these gaps, this research aims to demonstrate how such systems can optimize energy use, reduce grid dependency, and contribute to more sustainable energy consumption practices.

Recent studies have attempted to integrate EVs with PV systems using various approaches, including rule-based energy management systems, time-of-use scheduling, and basic IoT monitoring frameworks. However, these implementations often face limitations such as lack of dynamic responsiveness, limited user interface for control, or poor scalability when applied to real-time scenarios. For example, many systems rely solely on threshold-based switching, which does not adapt well to fluctuating solar irradiance and EV charging demands. Furthermore, few studies have integrated a web-based IoT control layer that allows users to monitor and adjust system performance remotely. These gaps highlight the need for a more adaptive, user-accessible, and accurate system for building-level PV-EV integration.

The economic feasibility of integrating rooftop solar systems with EVs has been well-documented, particularly in urban environments where space and energy demands create unique challenges [4], [5]. While prior analyses highlight the potential cost savings and environmental benefits of EVs and rooftop solar systems, challenges remain in optimizing energy usage at the building level. For instance, real-time energy management to balance solar, grid, and battery storage, as well as seamless integration of these sources, requires advanced control systems that are not yet widely implemented [6]. Additionally, the initial investment costs and the technical complexity of integrating renewable energy systems with battery management technologies often deter wider adoption, especially for small-scale applications [7]. Research further shows that homeowners with EVs are more likely to adopt rooftop solar systems, recognizing the complementary benefits of reduced energy costs and environmental sustainability [8]. This creates an opportunity to enhance urban sustainability by leveraging IoT-based energy management systems that promote energy self-consumption and reduce grid dependency [9]. Addressing these challenges, this study focuses on designing a localized energy management system to optimize the synergy between EVs and rooftop PV systems, ensuring economic and environmental benefits at the building scale.

The integration of EVs with rooftop PV systems offers a localized and scalable solution to enhance energy sustainability and reduce greenhouse gas emissions. While governments worldwide are promoting EV adoption and renewable energy integration, challenges such as limited charging infrastructure, high upfront costs, and consumer concerns about reliability persist [10], [11]. Rooftop PV systems, with their potential to generate significant solar energy-averaging 4.8 kWh/m² per day in many regions offer an effective approach to address these challenges by enabling self-consumption and reducing dependency on grid power [12]. The synergy between EVs and rooftop solar installations provides an opportunity to enhance energy resilience at the building level while supporting global climate goals such as net-zero emissions.

This research focuses on the development of an IoT-based energy management system to optimize the integration of rooftop PV systems, battery storage, and EV charging. By addressing gaps in real-time energy management and ensuring efficient utilization of renewable energy sources, the proposed system aims to overcome key barriers to adoption. This approach not only aligns with global sustainable energy targets but also demonstrates the viability of building-level solutions to advance renewable energy integration and electric mobility. The integration of EVs with rooftop PV systems in Indonesia, for example, offers significant opportunities for local job creation and economic development within the renewable energy sector [13]. Moreover, leveraging Indonesia's abundant natural resources, such as nickel for battery production, will be crucial as the country seeks to position itself as a key player in the Southeast Asian EV market [14].

INTERNET OF THINGS BASED EV ENERGY MANAGEMENT SYSTEM

The use of embedded systems in EV charging stations significantly enhances their efficiency and functionality. For instance, the integration of a Raspberry Pi enables intelligent monitoring and control of the charging process, ensuring optimal utilization of available energy resources while improving user experience through real-time data visualization on a web-based interface [15]. This capability not only streamlines the charging process but also enhances accessibility, allowing users to monitor system performance remotely. Additionally, the implementation of embedded systems in charging stations facilitates secure authentication methods, ensuring seamless interaction between users and the charging infrastructure [16]. Such advancements are essential for the development of smart charging solutions that adapt to the dynamic energy demands of EVs.

Moreover, the scalability of fast EV charging stations can be significantly improved through the use of cost-effective embedded systems, which enable efficient regulation and integration of solar energy and grid-based charging mechanisms [17]. These systems can execute advanced control algorithms to manage charging currents dynamically, optimizing energy distribution while maintaining system stability [18]. Furthermore, real-time charging optimization through web-based platforms provides users with critical information regarding charge status, energy consumption, and station availability, facilitating informed decision-making for EV users [19]. As the demand for EV infrastructure continues to expand, the role of embedded systems in enhancing the reliability and intelligence of charging stations will be crucial in supporting the transition to sustainable electric mobility.

The Raspberry Pi offers several advantages over other IoT microcontrollers, including robust processing capabilities and extensive connectivity options, making it well-suited for advanced IoT applications [20]. With built-in Wi-Fi and Ethernet support, it ensures seamless data communication and remote access without the need for additional modules, simplifying system design and reducing costs. Additionally, the Raspberry Pi features multiple USB ports and GPIO pins, enabling integration with various sensors and peripheral devices for comprehensive monitoring and control [21]. Its ability to handle more complex computational tasks allows for real-time data processing and decision-making, which is particularly beneficial for energy management in solar-powered systems [22]. Furthermore, the Raspberry Pi benefits from strong community support and a vast repository of open-source software, facilitating efficient development and deployment of IoT solutions [23]. These attributes make it a highly effective choice for optimizing energy management in IoT-based photovoltaic and battery storage systems, particularly in electric vehicle charging infrastructure.

This study aims to enhance EV charging stations by integrating IoT technology, utilizing a Raspberry Pi-based system for real-time monitoring and intelligent energy management. The implementation optimizes the operation of PV systems and battery storage by efficiently regulating energy flows, ensuring maximum utilization of solar power while maintaining stable charging and discharging cycles. This approach enables adaptive energy management strategies that align with fluctuating energy generation and demand, prioritizing renewable energy for EV charging whenever available. Additionally, the web-based monitoring platform provides users with real-time insights into charging status, energy availability, and system performance, improving accessibility and decision-making. By leveraging IoT-driven automation and data analytics, the proposed system enhances energy efficiency, reduces dependency on grid power, and contributes to a more sustainable and cost-effective EV charging infrastructure.

METHOD AND SYSTEM DESIGN

The method and system design of the proposed solution are described in this section, detailing both the operational logic and the physical components of the integrated solar PV and grid-connected system. The operational workflow is illustrated in Figure 1, which presents a structured decision-making process implemented in the Raspberry Pi using a rule-based control logic coded in Python. The system operates continuously with a 5-second refresh interval, enabling real-time responses to changing environmental and load conditions. It monitors two critical parameters: solar irradiation intensity and battery state of charge (SoC). When the SoC is within the optimal range (between 100%–15%) and solar irradiance exceeds 50 W/m², the system operates in a charging-discharging mode, directly supplying energy for EV charging while disabling the grid connection. If the SoC drops to a critical threshold of 10%, the system deactivates PV utilization and enables grid power through an Automatic Transfer Switch (ATS), ensuring uninterrupted energy supply while preventing deep discharge conditions that may shorten battery lifespan. Additionally, the system halts charging when SoC exceeds 95% to avoid overcharging. This priority logic ensures that solar energy is maximally utilized while maintaining battery health and overall system stability.

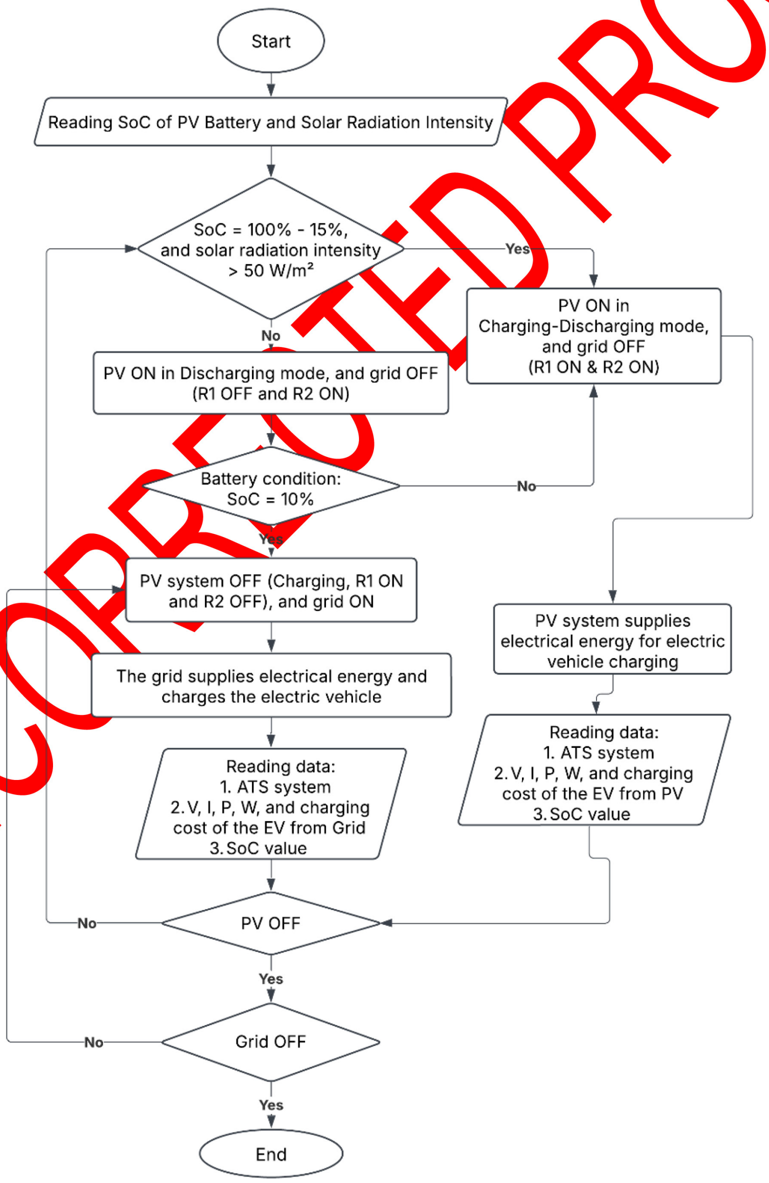

Figure 1. Flowchart of System Design

The overall structure and key hardware components of the proposed system are illustrated in Figure 2. The system integrates several crucial elements to facilitate smart energy management and dual-source switching. It comprises a VRLA battery (12V, 100Ah), a solar charge controller, an inverter, an Automatic Transfer Switch (ATS), and a MK2P-I relay. The MK2P-I relay plays a pivotal role in enabling automatic switching between solar and grid sources, always prioritizing solar power when available. Solar energy harvested by the photovoltaic panel is regulated by the charge controller before being stored in the battery. The inverter then converts DC energy to AC, making it suitable for powering various AC loads in both residential and industrial applications. The Battery Management System (BMS) embedded in the design uses the Coulomb Counting (CC) method to accurately estimate battery SoC in real time, thereby extending battery lifespan by preventing both overcharging and deep discharging scenarios. The switching operations coordinated between PV, battery, and grid ensure a smooth transition of power sources without interrupting supply.

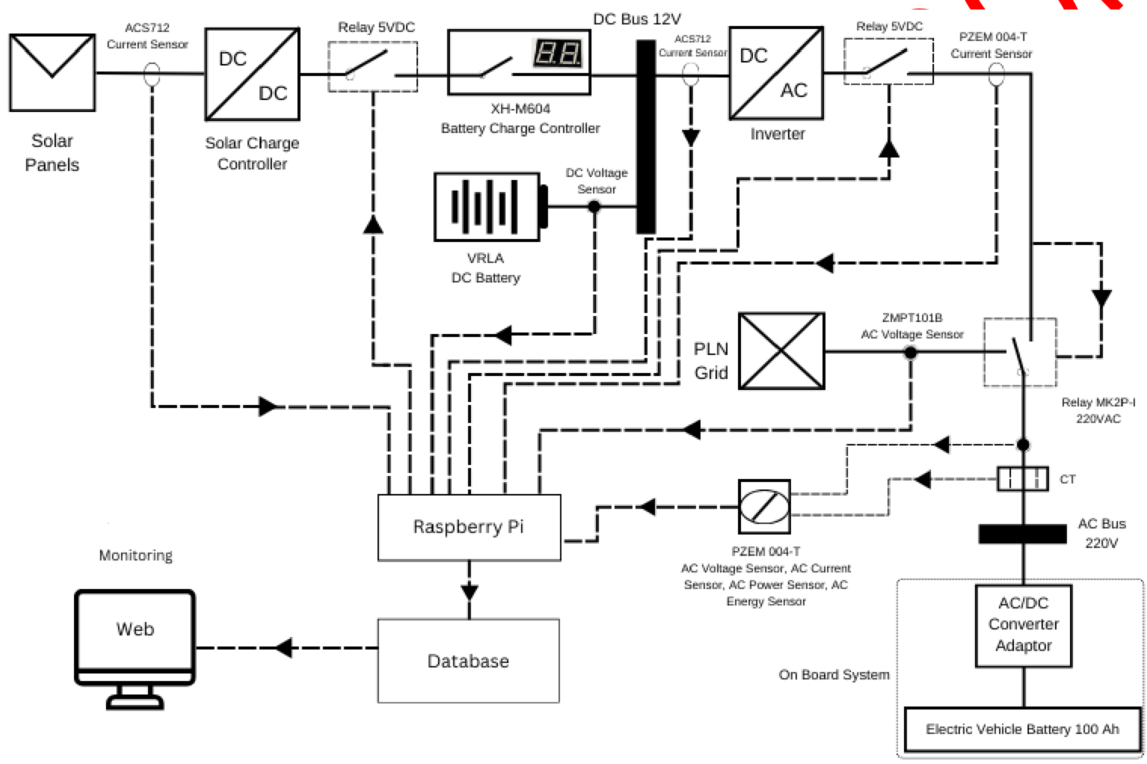

Figure 2. Block Diagram of System Design

Furthermore, the system is enhanced with an onboard electric vehicle (EV) charging mechanism, expanding its applicability in the context of sustainable transportation. The EV charging module uses an AC-DC converter with an input of 220VAC/50Hz and an output of 12V at 2.25A, ensuring a stable and efficient charging process. The entire system is monitored and controlled by a Raspberry Pi, which serves as the central processing unit. Real-time data acquisition is carried out using ACS712 and PZEM-004T sensors, which collect critical parameters such as voltage, current, power, energy consumption, and charging costs. This data enables precise control decisions and logging for future performance evaluation. The integration of all these components and control strategies results in an intelligent, adaptive energy management system that not only supports renewable energy integration and grid reliability but also offers support for EV charging, making it a comprehensive solution for smart energy applications.

Building upon this framework, the system incorporates an array of sensors and control mechanisms to optimize energy flow and ensure seamless operation. As depicted in Figure 3, the Raspberry Pi 5 functions as the central hub, managing data acquisition from key sensors, including ACS712 for current measurement, a VDC sensor for voltage monitoring, and PZEM-004T for tracking power, energy, and electricity costs during EV charging. The integration of a pyranometer and anemometer further enhances system intelligence by providing real-time environmental data, ensuring that energy production forecasts align with prevailing solar and wind conditions. A DHT11 sensor is also employed to monitor ambient temperature and humidity, parameters that influence battery efficiency and overall system performance.

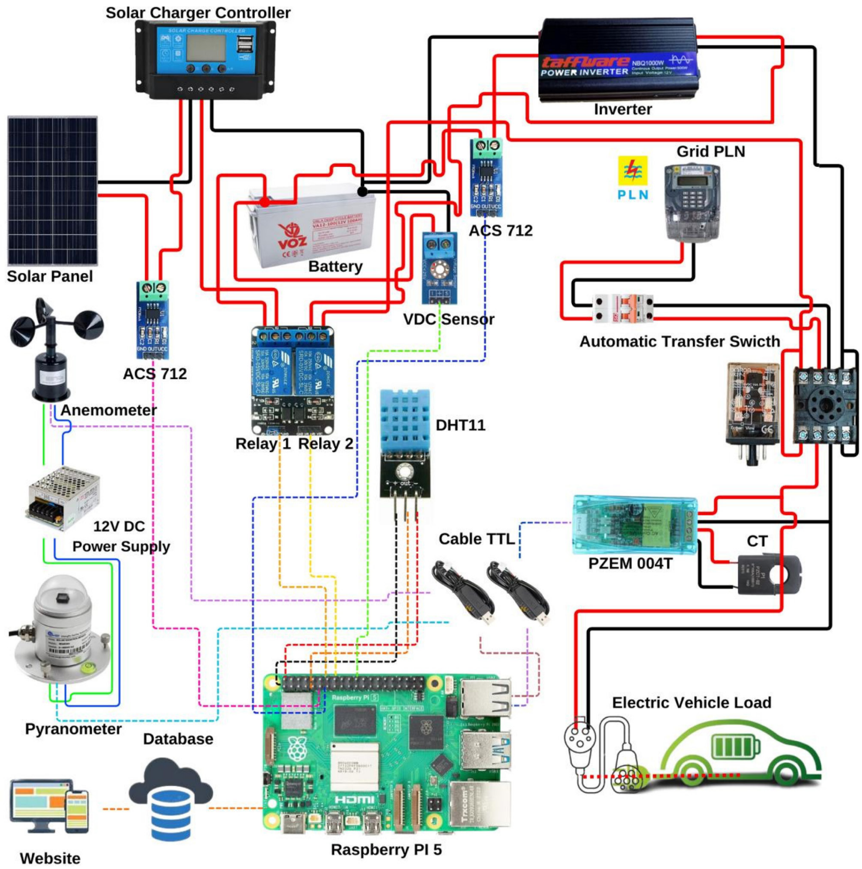

Figure 3. Wiring diagram of System Design

To maintain uninterrupted energy availability, the system employs a dual-channel relay module alongside the MK2P-I relay, facilitating controlled power distribution between solar, battery, and grid sources. The ATS ensures smooth transitions when solar energy is insufficient, while the solar charge controller regulates battery charging cycles to prevent overvoltage and deep discharge scenarios. The inverter efficiently converts stored DC power into AC for household loads and EV charging, ensuring compatibility with conventional power systems. By continuously monitoring energy parameters and battery conditions, the system dynamically adjusts power allocation, maximizing renewable energy usage while mitigating potential inefficiencies.

For enhanced user accessibility, an IoT-enabled web interface has been deployed, enabling remote system monitoring and control. Through a centralized database, real-time and historical data on power generation, energy consumption, and system efficiency can be accessed, allowing users to optimize their energy utilization strategies. The web interface replaces traditional mobile applications, offering a more comprehensive and user-friendly approach to energy management. By leveraging these integrated components and automation strategies, the proposed system not only enhances energy resilience but also reinforces the sustainable adoption of EV charging infrastructure powered by renewable energy sources.

RESULT AND DISSCUSSION

The results of this study demonstrate the successful implementation of a real-time web-based monitoring and control system for EV charging, utilizing Raspberry Pi 5 as the central processing unit. As illustrated in Figure 4, the web-based dashboard provides a user-friendly interface that displays real-time data on both weather conditions and the battery monitoring system, ensuring comprehensive supervision of the charging process. Key parameters such as solar irradiation (945 W/m²), wind speed (0.02 m/s), temperature (29°C), humidity (75%), and battery state of charge (95%) are continuously monitored and displayed. The system also tracks PV voltage (224.8 V), PV current (5.21 A), power consumption (37 W), and energy usage (0.01 kWh), allowing users to make informed decisions regarding energy consumption and system efficiency.

By integrating Raspberry Pi 5 with a web-based IoT platform, the system eliminates the limitations of mobile-based applications such as Blynk, providing a more scalable and accessible solution for real-time monitoring. The seamless transition between solar and grid power, as indicated by the system's ability to dynamically switch PV On / Grid Off, highlights its effectiveness in optimizing energy utilization. The dashboard's intuitive layout and automated data transfer functionality further enhance user engagement, ensuring that real-time insights into the charging infrastructure are readily available. Additionally, the system's ability to monitor charging costs (16.4 IDR) underscores its role in enabling cost-effective energy management, aligning with global sustainability objectives.

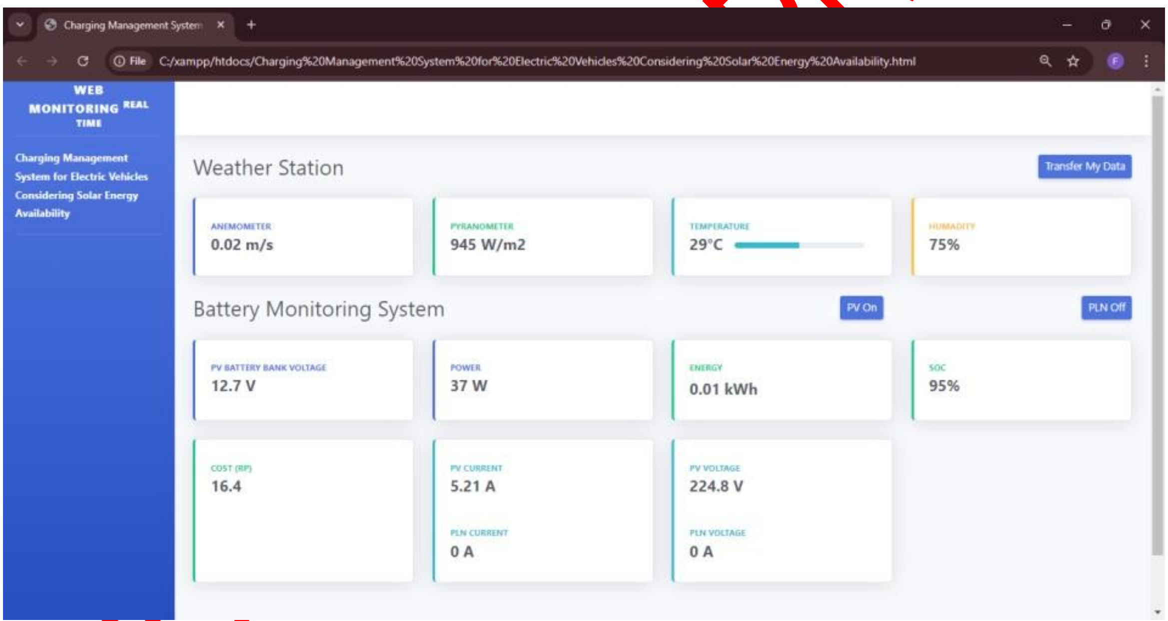

Figure 4. Electric Vehicle Charging Monitoring System View on the Website

Sensor calibration using a Fluke digital multimeter confirmed high measurement accuracy across all components. As shown in Table 1 and Table 2, the PZEM-004T voltage and current sensors exhibited low average errors of 0.126% and 0.356%, respectively, ensuring reliable AC measurements. Accurate power readings derived from these sensors are presented in Table 3, supporting their suitability for real-time power monitoring. For DC voltage calibration, Table 4 indicates a mean error of 0.247%, further demonstrating the sensor's precision. The SEM228A pyranometer, as shown in Table 5, achieved a low mean error of 0.177%, validating its performance in measuring solar irradiance.

Table 1. Voltage AC Sensor PZEM 004-T Accuracy

Voltage Sensor PZEM 004-T [V]	Multimeter [V]	Error [%]
221	221.1	0.045
221.3	221.7	0.180
221.6	221.8	0.090
221.4	221.7	0.135
221.2	221.6	0.180
	Mean	0.126

Table 2. Current Sensor PZEM 004-T Accuracy

Current Sensor PZEM 004-T [A]	Multimeter [A]	Error [%]
0.338	0.339	0.294
0.337	0.336	0.297
0.339	0.338	0.295
0.336	0.337	0.296
0.332	0.334	0.598
Mean		0.356

Table 3. Power AC PZEM 004-T

Voltage Sensor PZEM 004-T [V]	Current Sensor PZEM 004-T [A]	Power [W]
218.5	0.338	73.85
218.3	0.337	73.56
218.4	0.337	73.60
218.5	0.338	73.85
Mean		73.715

Table 4. Voltage DC Sensor PZEM 004-T Accuracy

Voltage Sensor PZEM 004-T [V]	Multimeter [V]	Error [%]
13.33	13.37	0.299
13.52	13.54	0.147
13.45	13.49	0.296
Mean		0.247

Table 5. SEM228A Sensor Accuracy

SEM228A Sensor [W/m^2]	Solar Power Meter [W/m^2]	Error [%]
1064	1060.4	0.339
1110	1108	0.180
1096	1111	0.013
Mean		0.177

The transition between power sources significantly impacts voltage stability, as evidenced by the shift from the PV system to the grid. When the PV system is active, the voltage remains steady at approximately 224 V, ensuring consistent power delivery. However, at 01:31 (GMT+7), a sudden transition occurs, where the grid takes over, causing the voltage to drop to around 219 V. This decrease, as shown in Figure 5, highlights the difference in voltage regulation between the two sources, demonstrating the grid's lower operating voltage. The noticeable drop underscores the need for careful management during power source transitions to maintain system stability.

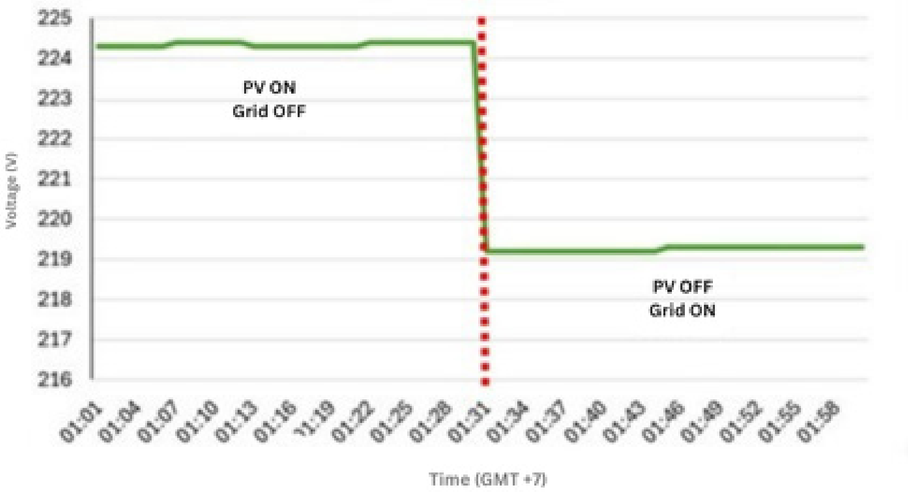

Figure 5. Voltage Transition from PV System to Grid

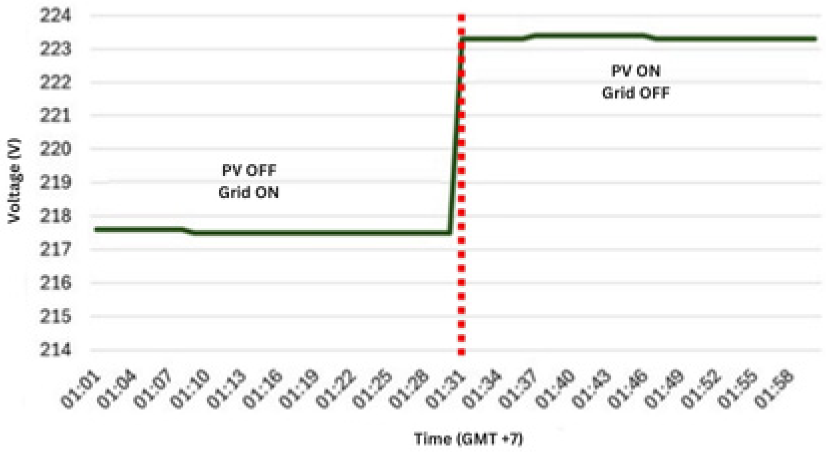

Figure 6. Voltage Transition from Grid to PV System

A shift from the grid to the PV system produces the opposite effect, demonstrating the PV system's ability to maintain a higher and more stable voltage. Initially, with the grid supplying power, the voltage remains at approximately 218 V. At 01:31 (GMT+7), the PV system takes over, resulting in a sharp voltage increase to around 224 V. This transition, depicted in Figure 6, showcases the PV system's superior voltage regulation compared to the grid. The smooth stabilization after the switch reinforces the PV system's reliability, highlighting its capability to provide a more stable power supply with minimal fluctuations.

Battery performance during charging and discharging is crucial for evaluating system efficiency. Initially, the battery is in a discharging state, with a stable current output of approximately 0 A. However, at 10:27 (GMT+7), as shown in Figure 7, the system transitions to charging mode, resulting in a significant increase in input current, peaking around 10 A. This indicates a rapid energy intake as solar power becomes available. The current remains relatively stable throughout the charging period, ensuring efficient energy absorption. However, after 15:00, the charging current begins to fluctuate and gradually decreases, reflecting the declining availability of solar energy as the day progresses.

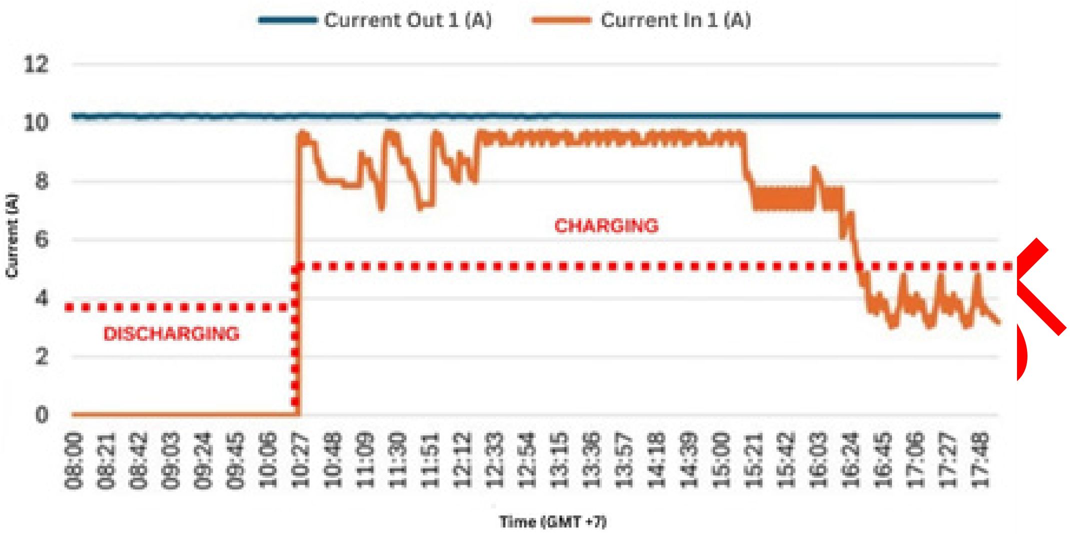

Figure 7. Battery Charging-Discharging Current Data Capture Graph

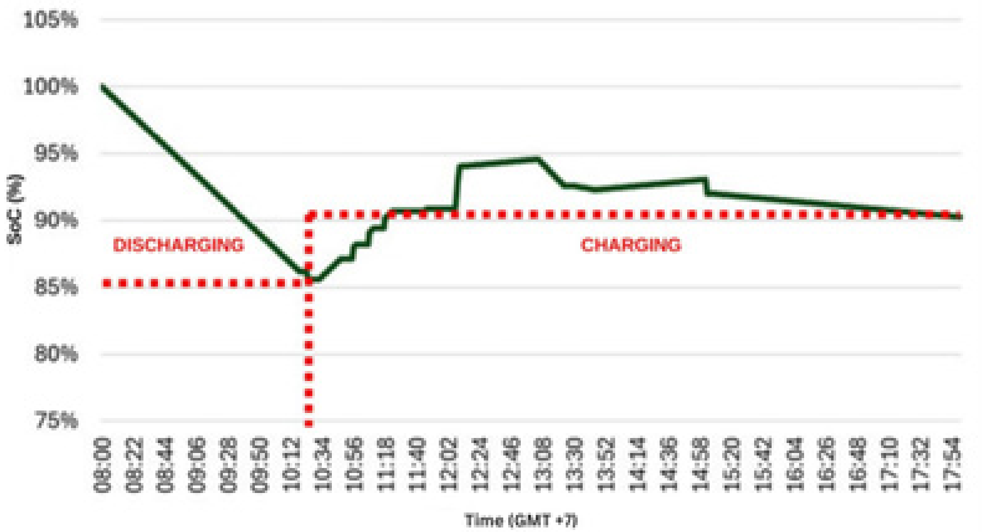

Figure 8. Battery Charging-Discharging SoC Data Capture Graph

State of Charge behavior further confirms the battery's charging and discharging patterns. Initially, the SoC declines steadily, reaching approximately 85% due to continuous discharging. At 10:12 (GMT+7), as depicted in Figure 8, the charging phase begins, leading to a gradual recovery in SoC. The battery regains its charge, stabilizing around 90%–95% throughout the midday period. Minor fluctuations in SoC suggest intermittent variations in solar power input. Later in the afternoon, the charging rate slows, and the SoC stabilizes before slightly decreasing, indicating reduced solar energy input and the transition toward evening discharge. These findings emphasize the effectiveness of solar charging while highlighting the dependency on solar availability.

The efficient management of battery charging and discharging plays a crucial role in ensuring optimal energy utilization, as previously demonstrated by the current and SoC analysis. The gradual charging process throughout the day allows the system to store sufficient energy, which is later utilized during periods of low solar availability. Figure 9 further reinforces this by illustrating the accumulation of energy primarily from the PV system, with a steady increase in stored energy until around 01:46 (GMT+7). At this point, the PV system is no longer capable of sustaining the load, and the grid takes over to maintain power availability. This transition underscores the importance of a well-managed storage system to maximize solar energy utilization and minimize dependence on the grid.

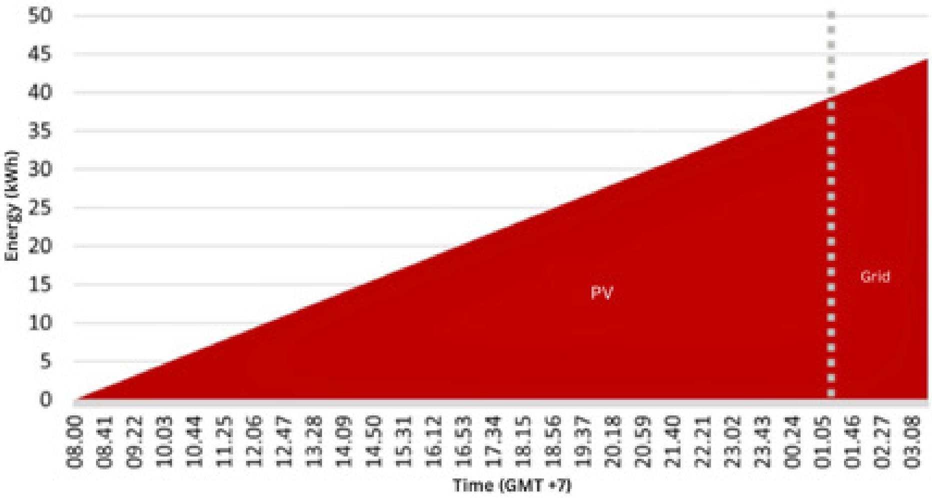

Figure 9. Energy in charging-discharging state with SoC Cut-Off 10%

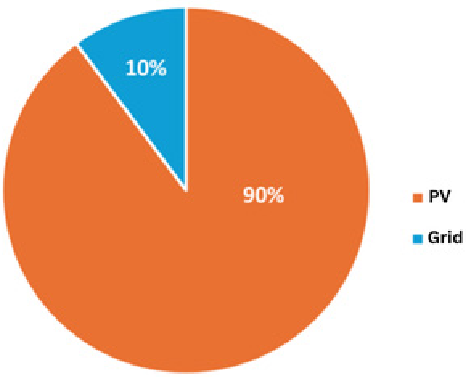

Figure 10. Distribution of energy consumption between PV vs Grid with SoC Cut-Off 10%

The effectiveness of PV integration in reducing grid reliance is evident when analyzing overall energy consumption. As seen in Figure 10, the PV system contributes 90% of the total energy supply, while only 10% is drawn from the grid. This high percentage of solar energy usage aligns with the stable SoC behavior observed earlier, confirming that the battery effectively stores and distributes energy throughout the day. The minimal reliance on the grid highlights the success of the PV system in sustaining power demands, further emphasizing the importance of optimizing solar energy storage to enhance energy independence. These findings collectively demonstrate how efficient battery management, stable SoC performance, and strategic energy distribution work together to maximize the benefits of solar power. While the proposed system demonstrates effective performance in a small-scale, building-level implementation, its scalability to larger applications warrants further consideration. In larger systems such as residential clusters, commercial facilities, or public charging networks several challenges may arise, including increased data traffic, latency in communication, and the need for more robust control algorithms. Additionally, geographic and climatic variability, such as differences in solar irradiance across regions or seasonal changes, may affect PV generation consistency and battery utilization strategies. To address these challenges, the current IoT framework can be enhanced through the integration of edge computing to process data locally and reduce latency, as well as AI-based forecasting methods to predict solar generation and load demand. Moreover, a modular system design would allow for easier expansion and adaptation to diverse deployment environments. Future studies should evaluate the system's performance in various climatic zones and explore interoperability with utility-scale demand response programs to assess its broader applicability.

CONCLUSION

The research findings confirm the successful implementation of an IoT-based energy management system that enables efficient switching between solar photovoltaic power and the utility grid. The integration of real-time monitoring through a web-based platform enhances system reliability by continuously tracking voltage, current, power, energy, and associated costs. The battery management system, utilizing the Coulomb Counting method, effectively regulates the charging and discharging processes, ensuring optimal battery performance and extended lifespan. The system maintains power delivery stability during EV charging, with the PV array providing a consistent charging current. Sensor calibration results further validate the accuracy of data acquisition, reinforcing the system's reliability for energy monitoring applications. The seamless integration of renewable energy sources, intelligent power switching, and IoT-based control establishes a robust framework for sustainable EV charging, contributing to the transition toward efficient and environmentally responsible energy solutions. For future research, the system can be extended by incorporating machine learning algorithms to forecast energy demand and solar generation, thereby improving scheduling and resource allocation. Additionally, integration with grid-level demand response programs could enhance flexibility and economic viability by enabling dynamic interaction with utility services. Field testing in larger-scale scenarios, such as residential communities or commercial facilities, is also recommended to evaluate the system's scalability, performance under diverse load conditions, and long-term operational feasibility in real-world environments.

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NOMENCLATURE

Abbreviations

IoT	Internet of Things
EVs	Electric vehicles
PV	Photovoltaic
SDGs	Sustainable Development Goals

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