Design of an Energy Management System for an Off-Grid Photovoltaic Agricultural Charging Station

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Abstract – **Off-grid photovoltaic (PV) systems require an effective Energy Management System (EMS) to ensure reliable power delivery while preventing excessive battery drain. However, many existing agricultural charging stations operate without intelligent monitoring and adaptive load management, resulting in inefficient energy utilization and battery performance degradation. This study presents the design and implementation of an EMS for an off-grid PV-powered agricultural charging station using an ESP32 microcontroller. The proposed system integrates a PZEM-017 sensor for monitoring DC parameters of the PV array and battery, a PZEM-004T sensor for AC load measurement, and a DS18B20 sensor for battery temperature monitoring. The Battery State of Charge (SoC) is estimated using the Coulomb Counting method, while a Mamdani Fuzzy Logic Controller determines the active load level based on the SoC, PV power, and load power. The operating mode is selected according to the power balance between PV generation and load demand. Experimental validation shows maximum measurement errors of 0.80%, 0.84%, and 2.74% for the PZEM-017, PZEM-004T, and DS18B20 sensors, respectively. The proposed energy management system (EMS) successfully performs adaptive load management by activating different load priority levels according to real-time energy conditions. Implementation on ESP32 yields identical decisions to the MATLAB reference model. Energy analysis shows a total PV generation of 66.68 kWh and a total load consumption of 20.66 kWh during the observation period, confirming that the available generation capacity exceeds the current energy demand. The proposed EMS improves battery protection, increases system reliability, and provides an adaptive strategy for managing energy in a standalone PV system.**

Keywords: Energy Management System, Off-grid Photovoltaic, Fuzzy Logic Controller, State of Charge, ESP32

I. Introduction

The growing demand for sustainable energy has accelerated the development of renewable energy technologies, particularly photovoltaic (PV) systems. Among various PV configurations, off-grid photovoltaic systems have become an effective solution for supplying electricity to remote locations where grid infrastructure is unavailable or economically impractical. These systems have been widely adopted in agriculture, rural electrification, telecommunications facilities, and remote communities because they can operate independently without relying on the conventional electricity grid [1], [2]. Unlike grid-connected systems, off-grid PV installations rely entirely on battery energy storage to maintain power continuity during periods of low solar radiation or nighttime operation. Consequently, battery performance is one of the most critical factors affecting system reliability. Overcharging and deep discharging can reduce battery life, decrease energy efficiency, and disrupt power availability for electrical loads. Therefore, an Energy Management System (EMS) is required to regulate the energy flow between the PV array, battery storage, and connected loads while maintaining battery operation within a safe operating range [3], [4].

An Energy Management System (EMS) performs real-time decision-making by monitoring the available energy from the photovoltaic array and the energy demand from the electrical load. Based on these conditions, the system determines whether the battery should be charged, discharged, or kept idle. Furthermore, the EMS can prioritize critical loads whenever the available energy becomes insufficient. This strategy not only improves energy utilization but also increases battery lifespan and overall system reliability [5].

Battery State of Charge (SoC) is one of the most important parameters in battery management because it represents the remaining available energy stored in the battery. Several estimation techniques have been developed, including the Open Circuit Voltage (OCV) method, the Kalman Filter, Artificial Neural Networks, and Coulomb Counting. Among these methods, Coulomb Counting is widely used for embedded applications due to its simple implementation, low computational complexity, and ability to continuously estimate SoC during the battery charging and discharging process [6], [7].

To enhance the decision-making capabilities of an EMS, many researchers have applied Artificial Intelligence (AI)-based control methods, particularly Fuzzy Logic Controllers (FLCs). Unlike conventional threshold-based controllers, FLC can accommodate uncertainties in renewable energy generation and load demand without requiring accurate mathematical models. As a result, fuzzy logic has become one of the most widely applied intelligent control methods for photovoltaic energy management systems [8].

Several previous studies have demonstrated the

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effectiveness of fuzzy logic in renewable energy applications. El Zerk and Ouassaid [9] proposed a real-time fuzzy energy management strategy for PV-Wind-Battery hybrid microgrids using a Hardware-in-the-Loop implementation. Their study demonstrated that fuzzy control successfully improved energy distribution under varying operating conditions. Samavat et al. [10] compared the Mamdani and Sugeno fuzzy inference systems for standalone photovoltaic applications and reported that both methods provided satisfactory energy management performance under fluctuating solar irradiance. Other studies have focused on IoT-based monitoring systems [11] and battery State-of-Charge estimation using the Coulomb Counting technique for photovoltaic systems [12].

Although previous studies have successfully demonstrated the application of EMS and fuzzy logic to renewable energy systems, most of these studies primarily focused on simulation environments, hybrid renewable energy systems, or monitoring platforms. Experimental implementations of intelligent EMS for existing off-grid photovoltaic systems with adaptive load prioritization based on real-world battery conditions are still relatively limited. Furthermore, many existing agricultural charging stations still operate without automatic energy management, resulting in inefficient utilization of available photovoltaic energy when load demand changes.

This study addresses these limitations by designing and implementing an Energy Management System for existing off-grid photovoltaic agricultural charging stations. Rather than redesigning the photovoltaic system, this study focuses on developing an adaptive EMS using an ESP32 microcontroller integrated with battery monitoring, photovoltaic monitoring, load monitoring, and a Mamdani Fuzzy Logic Controller. The battery state of charge is estimated using the.

II. METHODOLOGY

This study proposes an Energy Management System (EMS) for an existing off-grid photovoltaic agricultural charging station. The proposed methodology consists of system design, hardware implementation, energy management strategy, fuzzy logic controller development, battery State of Charge (SoC) estimation, and experimental validation. The Energy Management System is designed to regulate the energy flow between the photovoltaic array, battery, and electrical load while maintaining reliable system operation under varying power generation and load conditions. The overall methodology adopted in this study is described in the following subsections.

A. System Overview

This research was conducted on an existing off-grid photovoltaic (PV) power system used to supply electricity to an agricultural charging station. Rather than redesigning the PV installation, this study focused on developing an Energy Management System (EMS) capable of monitoring battery conditions and automatically managing load operation based on available energy. The proposed EMS is implemented using an ESP32 microcontroller integrated with voltage, current, power, temperature, and battery state-of-charge (SoC) monitoring.

The system consists of four main components: the photovoltaic array, battery energy storage, electrical load, and the proposed EMS. The photovoltaic array serves as the primary energy source, while the battery stores excess energy generated during daytime operation and supplies electricity when solar energy is unavailable. The EMS continuously monitors system parameters and determines the appropriate operating mode using a Mamdani Fuzzy Logic Controller (FLC).

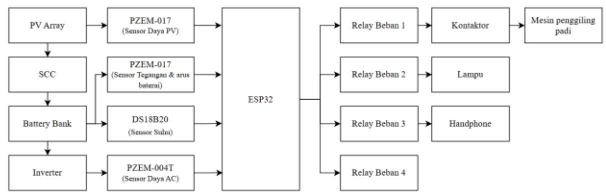


Figure 1. Overall Configuration of the Proposed Off-Grid Photovoltaic Energy Management System

The Energy Management System (EMS) determines operating conditions by evaluating the relationship between photovoltaic output power, battery SoC, and load demand. Based on these parameters, the controller automatically selects an appropriate load priority level to ensure the continuous operation of critical agricultural equipment while maintaining battery operation within a safe operating range. The overall system architecture shown in Figure 1 illustrates the interactions between the photovoltaic array, battery storage, electrical load, and the proposed Energy Management System. To realize this architecture, several hardware components are integrated to perform real-time data acquisition, system monitoring, and automatic load control.

B. Hardware Implementation

The proposed hardware platform consists of an ESP32 microcontroller, two PZEM-017 modules for DC electrical parameter measurement, one PZEM-004T module for AC load monitoring, and a DS18B20 digital temperature sensor for battery temperature measurement. A relay module is used to control load activation based on the fuzzy controller output.

The PZEM-017 sensor is installed to measure the photovoltaic voltage, current, and output power, as well as the battery electrical parameters. Meanwhile, the PZEM-004T module monitors the AC voltage, current, active power, and energy consumption of the connected load. Battery temperature is continuously measured using the DS18B20 sensor as an additional protection parameter for battery operation. The ESP32 periodically collects sensor data and runs a fuzzy inference algorithm in real time. Based on the calculated battery SoC and measured operating conditions, the controller generates load priority decisions by activating the appropriate relay outputs.

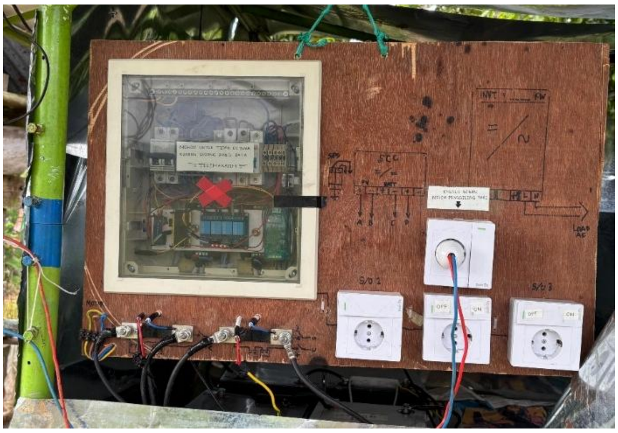


Figure 2. Hardware Implementation of the Proposed Energy Management System

Based on the implemented hardware configuration, an energy management strategy was developed to regulate power distribution among the photovoltaic array, battery storage, and connected loads. This proposed strategy aims to maintain energy balance while ensuring the continued operation of priority loads under various operating conditions.

C. Energy Management Strategy

The proposed Energy Management System regulates the power distribution between the photovoltaic array, battery, and electrical loads according to the available energy. Its operating principle follows the power balance relationship,

$$P_{PV} = P_{Load} + P_{Battery} \quad \text{.....................} (1)$$

where P_{PV} represents photovoltaic output power, P_{Load} denotes total load demand, and $P_{Battery}$ represents the battery's charging or discharging power.

When photovoltaic generation exceeds load demand, the excess energy is used to charge the battery. Conversely, when the generated power becomes insufficient, the battery supplies additional energy to maintain the uninterrupted operation of the connected loads. To improve battery utilization, electrical loads are classified into three priority levels based on operational importance. Rice milling machines are given the highest priority because they directly support agricultural productivity. Lighting loads are categorized as medium priority because they are needed during nighttime operations, while mobile phone charging loads are given the lowest priority due to their relatively flexible operating schedule.

D. Fuzzy Logic Controller Design

The Energy Management System uses a Mamdani Fuzzy Logic Controller to determine the active load level based on real-time operating conditions. Three input variables are selected: Battery State of Charge (SoC), photovoltaic output power, and load power demand. The controller produces two outputs: the battery operating mode (charging, discharging, or idle) and the active load level. The battery SoC is divided into three linguistic variables: Low, Medium, and High. Similarly, the photovoltaic power and load power are classified into Low, Medium, and High categories. Based on the combination of these input variables, fuzzy inference rules determine the most appropriate operating conditions. The fuzzy inference process consists of fuzzification, rule evaluation, aggregation, and centroid defuzzification. The resulting output is then transmitted to the ESP32 microcontroller, which controls the activation of relays based on the selected load priority.

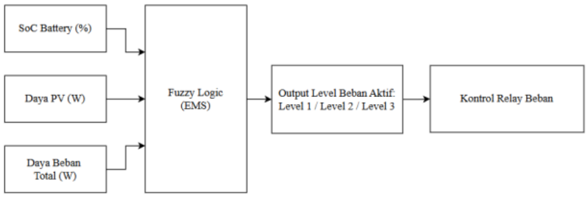
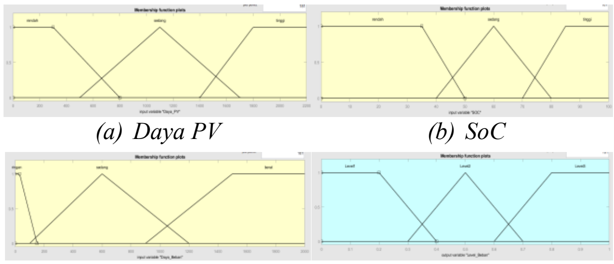


Figure 3. Mamdani Fuzzy Logic Controller Architecture



(a) Daya PV *(b) SoC*

(c) Daya Beban *(d) Output Level Sistem*

Figure 4. Membership Functions of Input and Output Variables

Since the battery state of charge (SoC) is one of the main input variables of the fuzzy controller, an accurate estimation method is required to continuously monitor the battery condition during system operation. Therefore, the Coulomb Counting method is adopted in this study because it provides continuous SoC estimation during the charging and discharging process.

E. Battery State of Charge Estimation

The Battery State of Charge (SoC) is estimated using the Coulomb Counting method because it allows continuous SoC calculation during the charging and discharging processes without interrupting system operation. The estimation is performed using the accumulated battery current according to

$$SOC(t) = SOC(t_0) \pm \frac{1}{C_n}\int_{t_0}^{t} I\ dt \quad \text{..............} (2)$$

where $SOC_{initial}$ is the initial State of Charge, C_n is the nominal battery capacity (Ah), $i(t)$ is the battery current, and t is the charging or discharging duration. The battery current is added during the charging process and subtracted during the discharging process. The estimated SoC is then used as one of the input variables for the fuzzy logic controller.

After system development, experimental testing was conducted to evaluate the overall performance of the proposed Energy Management System. The testing procedure focused on validating sensor accuracy, fuzzy logic implementation, battery charging behavior, and overall energy performance under actual operating conditions.

F. Experimental Procedure

The proposed energy management system (EMS) was experimentally evaluated using an existing off-grid photovoltaic system under actual operating conditions. Sensor measurements were automatically recorded at regular intervals and stored for later analysis.

System performance was evaluated using four performance indicators:

1. Measurement accuracy of the PZEM-017, PZEM-004T, and DS18B20 sensors.
2. Consistency between the fuzzy decision algorithm implemented on the ESP32 and the MATLAB simulation.
3. Battery charging and discharging characteristics based on state-of-charge variations.
4. Overall energy performance, including photovoltaic energy generation, load energy consumption, and energy utilization efficiency.

III. RESULTS AND DISCUSSION

The proposed Energy Management System (EMS) is experimentally evaluated to assess its performance under actual operating conditions. This evaluation focuses on four aspects: sensor measurement accuracy, fuzzy logic controller implementation, battery charging and discharging characteristics, and overall energy performance. The obtained results are analyzed to verify the effectiveness of the proposed EMS in maintaining battery operation and regulating power distribution in an off-grid photovoltaic system.

A. Sensor Performance Evaluation

Prior to evaluating the proposed Energy Management System (EMS), the accuracy of the measurement devices was verified to ensure reliable data acquisition during system operation. The developed EMS uses two PZEM-017 modules for DC electrical parameter measurements, one PZEM-004T module for AC load monitoring, and a DS18B20 sensor for battery temperature measurement. The measured values were compared with reference instruments under various operating conditions.

Validation results showed that all sensors provided satisfactory measurement accuracy. The PZEM-017 module achieved a maximum error of 0.80% for voltage measurements and 0.84% for current measurements, while the PZEM-004T module demonstrated a maximum error of 0.84% for AC load monitoring. Battery temperature measurements using the DS18B20 sensor yielded a maximum deviation of 2.74% compared to the reference thermometer. These results demonstrate that the proposed monitoring system meets the accuracy requirements for real-time implementation in an off-grid photovoltaic energy management system.

The relatively low measurement error confirms that the obtained data can be reliably utilized as input variables for a fuzzy logic controller without incurring significant decision-making errors. The obtained measurement errors indicate that the proposed monitoring system provides sufficiently accurate electricity and temperature measurements for real-time energy management applications. Reliable sensor measurements are crucial because inaccurate input data can lead to inappropriate fuzzy decisions, which affect battery protection and load management. Therefore, the achieved measurement accuracy indicates that the selected sensors are suitable for implementing the proposed EMS in practical off-grid photovoltaic applications..

B. Performance of the Energy Management System

The proposed Energy Management System (EMS) is implemented on an ESP32 microcontroller and evaluated under actual operating conditions. The controller continuously monitors photovoltaic power, battery state of charge (SoC), battery temperature, and load power before determining the operating mode and load priority level. The developed EMS successfully classifies the system's operating conditions into charging, discharging, and idle modes based on the available photovoltaic power and battery condition. When the photovoltaic output exceeds the load demand, the EMS allows battery charging while maintaining load operation. Conversely, during periods of insufficient photovoltaic generation, the battery supplies the energy needed to maintain uninterrupted load operation.

The fuzzy controller also manages three different load priority levels. The rice milling machine is given the highest priority because it directly supports agricultural activities. The lighting load is categorized as medium priority, while the mobile phone charging load is classified as low priority. This prioritization strategy allows the EMS to disconnect low-priority loads whenever the available energy becomes insufficient, thereby protecting the battery from excessive discharge.

The implementation results show that the proposed EMS is capable of performing automatic energy management according to real-time operating conditions, ensuring continuous operation of priority loads while maintaining battery availability.

During experimental observations, the EMS continuously adjusts its operating decisions according to changes in photovoltaic generation and load demand. When solar energy generation is sufficient, the controller maintains battery charging while simultaneously supplying electrical loads. Conversely, when photovoltaic output decreases, the EMS automatically switches to battery-powered operation without interrupting power delivery to priority loads. These results demonstrate that the proposed control strategy successfully maintains system stability under varying operating conditions.

C. *Validation of the Fuzzy Logic Controller*

To verify the correctness of the embedded implementation, the fuzzy logic controller executed on the ESP32 was compared with the MATLAB Fuzzy Logic Toolbox.

Table III. Comparison Between MATLAB and ESP32 Fuzzy Decisions

P_PV (W)	SoC (%)	P_Beban (W)	Level Value (ESP32)	Level Value (MATLAB)
125,7	100	17,6	0,844	0,847
622,9	100	658,0	0,622	0,624
603,6	100	644,7	0,603	0,605
0	99,30	720,7	0,500	0,500
0	98,90	698,8	0,500	0,500
234,2	98,88	632,1	0,500	0,500
243,7	98,91	5,0	0,844	0,847

The comparison shows that each fuzzy decision generated by the ESP32 is identical to the corresponding MATLAB output for all evaluated test scenarios. These results confirm that the embedded implementation accurately represents the designed Mamdani Fuzzy Logic Controller and can reliably execute energy management decisions in real-time. The consistency between the simulation and the hardware implementation indicates that the proposed EMS can perform adaptive decision-making without requiring continuous communication with an external computing device.

D. *Battery Charging and Discharging Characteristics*

Battery State of Charge (SoC) was analyzed to evaluate charging and discharging characteristics during actual system operation.

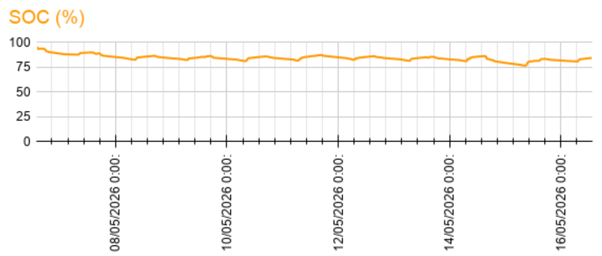


Figure 7. Battery State of Charge During the Observation Period

As shown in Figure 7, the battery SoC fluctuated between 86.90% and 96.03% throughout the observation period. Unlike conventional battery charging systems, the battery does not return to 100% because the charging and discharging processes occur alternately according to photovoltaic generation and load demand. To further analyze the battery behavior, the charging and discharging periods were identified based on the SoC variation.

Table IV. Battery Charging and Discharging Characteristics

Date	Condition	Time Interval	SOC (%)	Duration
19 June	Charging	07.15-17.35	86,90 - 92,91	10h 20min
19-20 June	Discharging	17.35-07.00	92,91 - 91,87	13h 25min
20 June	Charging	07.00-17.00	91,87 - 94,87	10h
20-21 June	Discharging	17.00-07.00	94,87 - 93,64	14h

The effective charging period is approximately 10 hours per day, while the battery discharge occurs approximately 13–14 hours per day. The lowest SoC value of 86.90% was recorded on June 19, 2026, at 07:15, after which the battery gradually recovered and reached 94.87% on June 20, 2026, at 17:00. Consequently, the recovery process from the minimum SoC to the highest observed value took approximately 33 hours and 45 minutes, consisting of alternating charge and discharge cycles. These observations indicate that the EMS successfully maintained battery operation within a safe operating range while continuing to supply electrical energy to the connected load.

E. *Energy Performance Analysis*

Cumulative photovoltaic energy generation and load energy consumption were evaluated to determine the overall effectiveness of the proposed EMS.

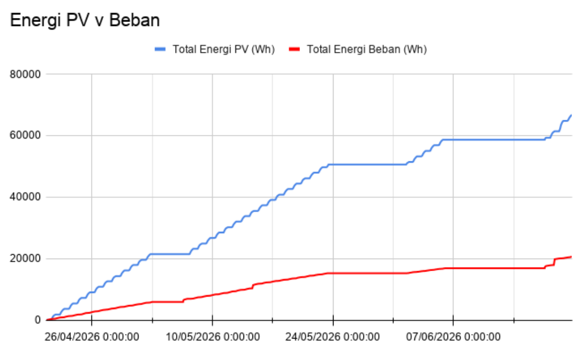


Figure 5. Cumulative Energy Produced by the PV System and Energy Consumed by the Load

During the observation period, the photovoltaic system generated a total of 66.68 kWh of energy, while the connected loads consumed 20.66 kWh. The cumulative energy difference of 46.02 kWh indicates that the available photovoltaic generation exceeded the actual load demand.

It should be noted that the calculated energy difference does not represent the energy stored in the battery. Rather, it represents the cumulative difference between photovoltaic generation and load consumption over the observation period. Since the battery capacity is limited to 19.2 kWh, excess energy beyond the allowable charging capacity is regulated by the Solar Charge Controller (SCC) through a charge limitation mechanism.

Overall, the experimental results show that the proposed EMS effectively balances photovoltaic generation, battery storage, and electrical loads while protecting the batteries and maintaining reliable system operation. The obtained energy utilization ratios indicate that the existing photovoltaic installation has a significantly higher generation capacity than the current energy demand. Consequently, the batteries achieve a high charge level during most of the operating period, allowing the EMS to keep all priority loads active. These results also indicate that the proposed system has sufficient reserve capacity to accommodate additional electrical loads in future agricultural applications without requiring major modifications to the existing photovoltaic installation.

IV. CONCLUSION

This study presents the design and implementation of an Energy Management System (EMS) for an existing off-grid photovoltaic agricultural charging station using an ESP32 microcontroller and a Mamdani Fuzzy Logic Controller. The proposed EMS successfully integrates photovoltaic monitoring, battery monitoring, load monitoring, and battery temperature measurement into a single embedded platform capable of real-time energy management. Experimental results demonstrate satisfactory measurement accuracy, with maximum errors of 0.80%, 0.84%, and 2.74% for the PZEM-017, PZEM-004T, and DS18B20 sensors, respectively. Furthermore, the fuzzy logic implementation on the ESP32 produces decisions consistent with the MATLAB reference model, confirming the reliability of the proposed control algorithm.

The developed EMS effectively regulates battery charging and discharging while automatically prioritizing electrical loads based on the Battery State of Charge, photovoltaic output power, and load demand. During the observation period, the photovoltaic system generated 66.68 kWh of electrical energy, while the connected loads consumed 20.66 kWh, indicating that the available generation capacity was sufficient to support the existing load demand. Overall, the proposed Energy Management System improves battery protection, optimizes energy utilization, and enhances the operational reliability of the off-grid photovoltaic system.

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