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Short Communication

Design of an IoT-Based Solar Energy Storage System Using $LiFePO_4$ Batteries for Sustainable Agricultural Irrigation

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Abstract

The increasing demand for sustainable Agricultural Irrigation requires an efficient and reliable energy supply. This study presents the design of an Internet of Things (IoT)-based Solar Energy Storage system using Lithium Iron Phosphate ($LiFePO_4$) batteries to support Agricultural Irrigation. The system utilizes solar photovoltaic (PV) panels as the primary energy source, while $LiFePO_4$ batteries are used to store electrical energy for operating the irrigation pump when Solar Energy is insufficient. An ESP32 microcontroller is implemented to monitor and record battery voltage, current, temperature, and energy consumption in real time. The system is designed to improve the utilization of Solar Energy, provide reliable power for irrigation, and reduce dependence on conventional electricity sources. The performance of the proposed system is evaluated through simulation based on generation, battery charging and discharging performance, energy efficiency, and irrigation operation. The proposed system is expected to provide a sustainable and intelligent energy solution for small-scale Agricultural Irrigation.

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1. Introduction

Agricultural irrigation is an essential process for maintaining crop growth and productivity, particularly in areas where water availability is limited or rainfall is irregular. Conventional irrigation systems generally depend on grid electricity or fuel-powered generators, which can increase operating costs and contribute to greenhouse gas emissions. The use of renewable energy, particularly solar photovoltaic (PV) technology, has therefore become an attractive alternative for supplying energy to agricultural irrigation systems. Solar-powered irrigation systems can utilise solar energy during daytime operation and reduce dependence on

conventional electricity sources [1]. However, the intermittent nature of solar energy remains a challenge because PV power generation varies depending on solar irradiance and weather conditions.

Several studies have developed solar-powered irrigation systems integrated with Internet of Things (IoT) technology to improve irrigation control and monitoring. IoT-based irrigation systems commonly utilise sensors to monitor soil moisture, environmental conditions, water flow, and system operating parameters, allowing irrigation to be controlled according to crop requirements [2,3]. The integration of solar PV with IoT technology can improve the efficiency of agricultural water management while providing real-time monitoring of system conditions. In addition, previous research has demonstrated that solar-powered pumping systems can provide sufficient energy for small-scale agricultural applications when the PV system is properly designed according to the required load [4,5]. However, the availability of solar energy is not always consistent with irrigation demand, especially during cloudy conditions, night-time operation, or periods of low solar irradiance.

Energy storage is therefore an important component for maintaining the reliability of solar-powered irrigation systems. Lithium iron phosphate ($LiFePO_4$) batteries have attracted considerable interest for energy storage applications because of their relatively long cycle life, good thermal stability, and suitability for repeated charging and discharging [3]. Previous studies have also implemented $LiFePO_4$ batteries in IoT-based renewable energy systems to store excess solar energy and provide power when solar generation is insufficient [3]. Nevertheless, most studies on smart agricultural irrigation have focused primarily on irrigation automation, soil-moisture control, and water efficiency, while the detailed performance of $LiFePO_4$ energy storage in supporting irrigation loads has received less attention.

The research gap addressed in this study is the limited evaluation of $LiFePO_4$ battery performance as the main energy storage component in an IoT-based solar irrigation system, particularly under variations in solar energy availability and irrigation load. Previous research has generally evaluated the overall performance of solar-powered irrigation or IoT-based control systems, but the relationship between PV generation, battery charging and discharging, state of charge (SOC), energy consumption, and irrigation operation requires further investigation [3–5]. The significance of this research lies in the development of an IoT-based solar energy storage system that combines solar PV generation, $LiFePO_4$ battery storage, and real-time monitoring for small-scale agricultural irrigation. The system is expected to improve solar energy utilisation and provide a more reliable energy supply for irrigation pumps. Therefore, this study aims to design and evaluate an IoT-based solar energy storage system using $LiFePO_4$ batteries for sustainable agricultural irrigation. The system performance is evaluated based on PV energy generation, battery charging and discharging characteristics, SOC variation, energy efficiency, and the ability of the stored energy to support irrigation pump operation under different solar energy conditions.

2. Methodology

2.1. System Configuration and Components

The designed system comprises a photovoltaic (PV) panel as the primary energy source, a solar charge controller (SCC) to regulate the charging process [6], a lithium iron phosphate ($LiFePO_4$) battery equipped with a battery management system (BMS) for energy storage [7], an irrigation pump operating as the electrical load, and an ESP32 microcontroller serving as the core data acquisition unit [8,9]. Energy generated by the PV panel charges the battery via the SCC. The stored energy is subsequently utilised to drive the irrigation pump during periods of insufficient solar irradiance. The ESP32 microcontroller is deployed to continuously record key operating parameters, including voltage, current, battery temperature, state of charge (SOC), and overall energy consumption [10,11]. The recorded parameters enable comprehensive characterisation of the energy storage dynamics and assess the battery capacity in meeting the power requirements of the agricultural pump. The technical specifications and parameters logged for each system component are outlined in Table 1.

Table 1. System components and recorded monitoring parameters.

No.	Component	Logged Parameters
1	PV Panel	Power, voltage, current, panel quantity
2	Solar Charge Controller (SCC)	Type, system voltage, rated current capacity
3	$LiFePO_4$ Battery	Nominal voltage, capacity (Ah), cell configuration
4	Battery Management System (BMS)	System voltage, current rating, protection features
5	ESP32 Microcontroller	Processing unit and monitoring platform
6	Voltage Sensors	PV voltage, battery voltage, load voltage
7	Current Sensors	PV current, battery current, load current
8	Temperature Sensor	Battery core/surface temperature
9	Irrigation Pump	Voltage, current, power consumption, operating time
10	LCD / Display Module	Real-time parameter visualisation

2.2. System Configuration

The operational architecture is structured into four functional stages: energy generation, charge regulation, energy storage, and irrigation load. The PV panel converts solar radiation into electrical power, which is redirected to the SCC to manage the $LiFePO_4$ charging profiles. The battery bank acts as a buffer, supplying electrical power to the irrigation pump whenever solar power drops below the load demand [12,13]. The ESP32 is integrated as an IoT monitoring unit to capture and store electrical and thermal parameters in real time [14,15]. The generalised power flow is illustrated as: 60 Wp PV panel - 10/15 A SCC - 4S 12.8 V $LiFePO_4$ battery + BMS - irrigation pump. Concurrently, the data collection flow is structured as: voltage + current + temperature sensors - ESP32 MCU - display/monitoring interface. The overarching system layout is presented in Figure 1 and Figure 2.

The physical layout and wiring setup of the solar energy storage prototype are in Figure 2. The primary power flow originates from the photovoltaic (PV) panel, which generates DC electricity from direct sunlight exposure. The positive and negative terminals of the PV panel are wired directly into the input power channels of the PWM solar charge controller (SCC). The SCC serves as the core power management unit, regulating the charging voltage and current level to ensure optimal energy transfer while preventing battery overcharging. The regulated output of the SCC is connected directly to the positive (+) and negative (−) terminals of the $LiFePO_4$ battery pack equipped with an integrated battery management system (BMS). This configuration forms the main power generation and storage backbone, enabling real-time telemetry parameters (such as PV voltage, charging current, and battery terminal voltage) to be sampled by the ESP32 microcontroller sensing network before power distribution to the irrigation pump load.

2.3. IoT-Based Monitoring System Architecture

The ESP32 microcontroller functions as the master controller for data acquisition. Precision voltage and current transducers are strategically positioned across the PV generation unit, battery terminal, and load side. A thermal sensor is directly attached to the battery pack to track temperature variations during continuous charging and discharging phases. Sensor signals are processed by the ESP32 and transmitted to an onboard LCD as well as an online telemetry dashboard. Real-time monitored parameters comprise voltage, current, power output, battery temperature, and SOC. This infrastructure facilitates precise evaluation of the interactions between solar availability, battery status, and pump energy demand. The hardware topology and sensing arrangement are depicted in Figure 3.

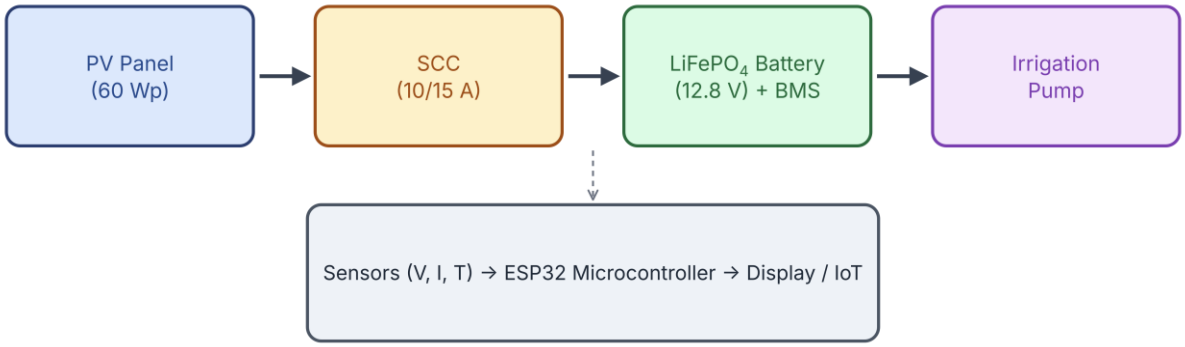


Figure 1. Block diagram of the IoT-based solar energy storage and monitoring system.

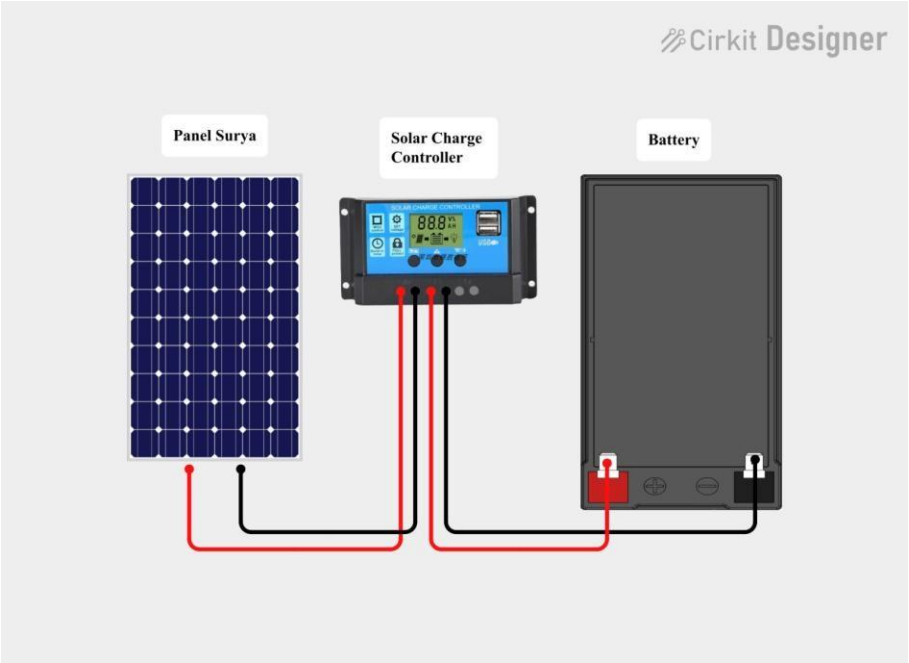


Figure 2. Wiring diagram and physical interconnection of the PV panel, solar charge controller (SCC), and $LiFePO_4$ energy storage unit.

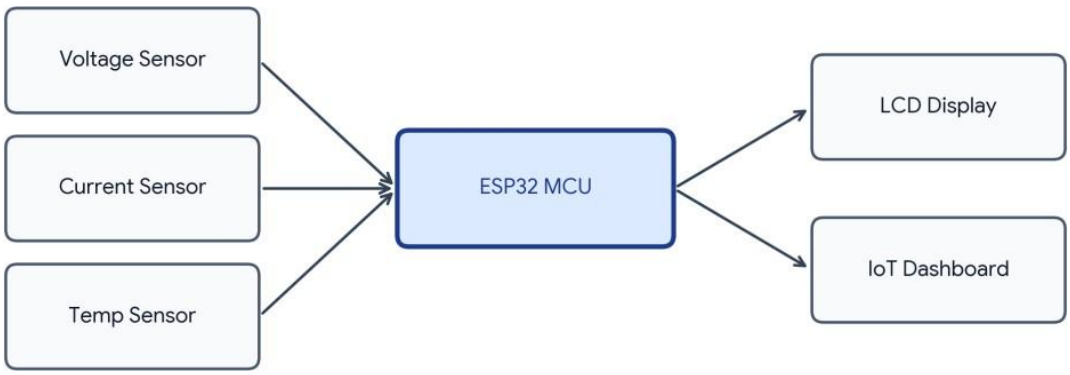


Figure 3. Hardware schematic and telemetry configuration.

2.4. Data Acquisition and Experimental Conditions

Data logging was conducted continuously at fixed sampling intervals ranging from 1 to 5 minutes. The collected dataset captures dynamic changes in system performance across energy generation, battery charge/discharge cycles, and active pumping periods. The specific environmental and electrical variables logged during testing are summarised in Table 2 and Table 3.

Table 2. Collected experimental parameters and measurement units.

Group	Parameter	Unit
PV Generation	PV Voltage (V_PV)	V
PV Generation	PV Current (I_PV)	A
PV Generation	PV Power (P_PV)	W
PV Generation	Solar Irradiance	W/m²
Battery Storage	Battery Voltage (V_Bat)	V
Battery Storage	Battery Current (I_Bat)	A
Battery Storage	Battery Temperature	°C
Battery Storage	State of Charge (SOC)	%
Pump Load	Pump Voltage (V_Pump)	V
Pump Load	Pump Current (I_Pump)	A
Pump Load	Pump Power (P_Pump)	W
Pump Load	Operation Runtime	min / h
System Energy	Cumulative PV Energy	Wh
System Energy	Cumulative Battery Energy	Wh
System Energy	Cumulative Pump Consumption	Wh

Table 3. Experimental test conditions and evaluation objectives.

Condition	Solar Availability	Battery Mode	Testing Objective
1	High Irradiance	Charging	Evaluate PV charging rate and efficiency
2	Medium / Low Irradiance	Charging / Discharging	Assess battery response under fluctuating solar power
3	Zero Irradiance (Night)	Discharging	Determine pure battery autonomy during night-time pumping
4	Load Variation	Discharging	Analyse SOC depletion rate under varying pump load demands

2.5. Data Processing and Mathematical Formulation

The raw telemetry dataset is processed to calculate instantaneous power, cumulative energy consumption, battery state of charge, conversion efficiencies, and system autonomy.

2.5.1. Power Calculation

Instantaneous electrical power is computed as the product of measured voltage and current, as expressed in Equation (1).

$$P = V \times I \tag{1}$$

where P represents electrical power (W), V denotes voltage (V), and I is current (A). Equation (1) is applied individually to calculate PV generated power, battery charge/discharge power, and pump power demand.

2.5.2. Energy Calculation

Energy consumption or generation over a given time interval is calculated using Equation (2).

$$E = P \times t \tag{2}$$

where E is energy (Wh), P is power (W), and t is operating duration in hours (h). For discrete time-series measurements with logging intervals Δt, total cumulative energy is computed via numerical integration as shown in Equation (3).

$$E_{total} = \sum \left(P_j \times \Delta t \right) \tag{3}$$

2.5.3. State of Charge (SOC) Estimation

Battery state of charge (SOC) indicates the remaining capacity percentage. SOC estimation is implemented using the Coulomb counting method [16–20], expressed in Equation (4).

$$SOC(t) = SOC(t-1) + \left[\frac{I \times \Delta t}{C_{nom}} \right] \times 100\% \tag{4}$$

where $SOC(t)$ represents SOC at time step t (%), SOC(t−1) is the previous state (%), I is current (A), Δt is the sampling interval (h), and $C_{nom}$is the nominal battery capacity (Ah). By convention, charging currents are assigned positive values, whereas discharging currents are negative.

2.5.4. Nominal Battery Energy

The total energy capacity of the battery pack is determined from nominal rating parameters using Equation (5).

$$E_{battery} = V_{nom} \times C_{nom} \tag{5}$$

where $E_{battery}$ is nominal battery energy (Wh), V_{nom} is nominal pack voltage (V), and C_{nom} is capacity (Ah).

2.5.5. Battery Charging Efficiency

Charging efficiency evaluates the proportion of PV energy successfully stored into the battery pack, as formulated in Equation (6).

$$\eta_{\text{charge}} = \frac{E_{\text{stored}}}{E_{\text{PV}}} \times 100\% \tag{6}$$

where η_{charge} is charging efficiency (%), E_{stored} is net energy added to the battery (Wh), and E_{PV} is total energy delivered by the PV array (Wh).

2.5.6. Overall System Efficiency

Overall system efficiency defines the fraction of generated solar energy effectively utilised by the pump load, as defined in Equation (7).

$$\eta_{\text{system}} = \frac{E_{\text{load}}}{E_{\text{PV}}} \times 100\% \tag{7}$$

where η_{system} is system efficiency (%), E_{load} is energy consumed by the pump (Wh), and E_{PV} is energy produced by the PV system (Wh).

2.5.7. Battery Autonomy Duration

The operational backup duration provided solely by the battery bank is evaluated via battery autonomy, calculated in Equation (8).

$$T_{\text{automony}} = \frac{E_{\text{usable}}}{P_{\text{pump}}} \tag{8}$$

where T_{autonomy} is continuous operating runtime (h), E_{usable} is usable battery energy considering depth of discharge limits (Wh), and P_{pump} is active pump power consumption (W).

2.5.8. Data Processing Workflow

The data processing pipeline executes sequentially from sensor data acquisition to comprehensive performance evaluation. Raw voltage and currently telemetry feeds into power and energy calculation, followed by SOC estimation, efficiency determination, and battery autonomy assessment. The sequential flow of data processing is depicted in Figure 4.



Figure 4. Sequential workflow of data processing and system performance evaluation.

3. Results

This section presents the empirical outcomes obtained from the experimental testing of the IoT-based solar energy storage and monitoring system prototype. It should be emphasised that all experimental evaluations were performed on a small-scale prototype setup designed for laboratory and field feasibility testing. The discussions encompass PV generation characteristics, sensor measurement accuracy, $LiFePO_4$ battery storage dynamics, overall system efficiency, and autonomy duration.

3.1. Prototype Photovoltaic Performance

The photovoltaic generation profile was evaluated outcomes across a representative 9-hour operational period (08:00-17:00). The prototype features a single 60 Wp panel. Peak power generation occurred near solar noon (12:00) when solar irradiance reached 950 W/m^2, yielding an installations maximum power output of 57.0 W. The representative measurement for power generation and solar irradiance across the test are summarised in Table 4.

Table 4. Measured solar irradiance and prototype PV output power across test time.

Time	Irradiance (W/m²)	PV Voltage (V)	PV Current (A)	PV Power Output (W)
08:00	280	17.5	0.96	16.8
10:00	680	17.8	2.29	40.8
12:00	950	18.1	3.15	57.0
14:00	750	17.7	2.54	45.0
16:00	310	17.2	1.08	18.6

The total cumulative energy generated by the 60 Wp prototype panel over the 9-hour observation period was computed using numerical integration according to Equation (9):

$$E_{total} = \sum \left(P_j \times \Delta t \right) = 328.2 \text{ Wh} \quad (9)$$

The direct relationship between solar irradiance and prototype PV output power is depicted in Figure 5.

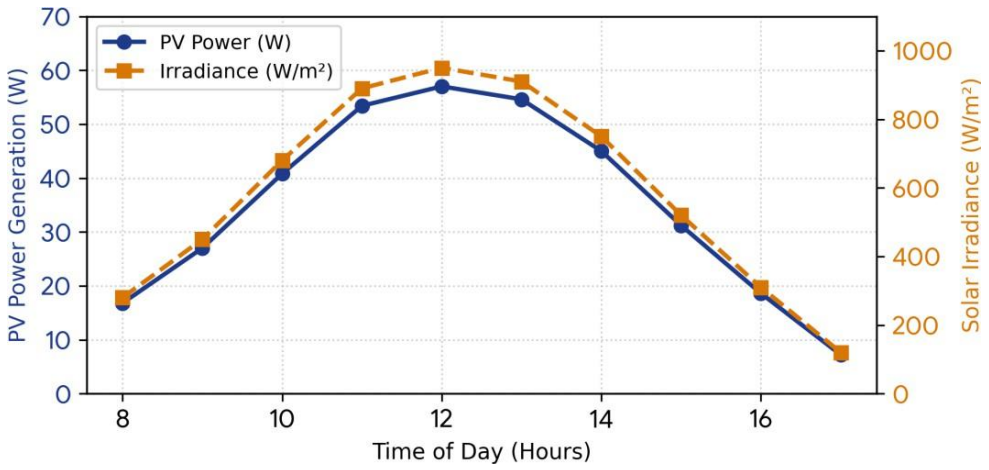


Figure 5. Prototype PV power generation profile and solar irradiance over the test period.

3.2. Sensor Measurement Accuracy and Display Parameters

To ensure reliable IoT monitoring, the measurement parameters computed by the ESP32 microcontroller were validated against calibrated benchtop reference instruments. Table 5 details the parameters recorded by the sensing network, including measurement ranges, display resolution, and average percentage error obtained during prototype testing.

Table 5. Sensor parameters, display specifications, and telemetry validation results.

Parameter	Sensor / Transducer	Measurement Range	Display Resolution	Avg. Error (%)
PV Voltage	Resistor Voltage Divider	0 – 25 V	0.01 V	0.82%
PV Current	ACS712-20A Hall Effect	0 – 20 A	0.01 A	1.15%
Battery Voltage	Resistor Voltage Divider	0 – 25 V	0.01 V	0.64%
Battery Current	ACS712-20A Hall Effect	-20 – +20 A	0.01 A	1.08%
Battery Temp.	DS18B20 Digital Sensor	-10 – 85 °C	0.1 °C	0.45%
Load Current	ACS712-05A Hall Effect	0 – 5 A	0.01 A	0.95%

3.3. $LiFePO_4$ Battery Storage and Autonomy Calculations

The prototype energy storage unit consists of a 4S $LiFePO_4$ battery pack with a nominal voltage of 12.8 V and a nominal capacity of 10 Ah. The nominal stored energy capacity is calculated according to Equation (10):

$$E_{battery} = V_{nom} \times C_{nom} = 12.8\ \text{V} \times 10\ \text{Ah} = 128.0\ \text{Wh} \tag{10}$$

To prevent accelerated battery degradation, a depth of discharge (DOD) limit of 80% was configured in the BMS software. Consequently, the usable battery energy for pump operation is derived as:

$$E_{\text{usable}} = E_{battery} \times \text{DOD} = 128.0\ \text{Wh} \times 0.80 = 102.4\ \text{Wh} \tag{11}$$

During Condition 3 testing (zero irradiance or night-time operating regime), the prototype irrigation pump operated at a measured average power draw of 24.0 W (12 V, 2 A). Applying Equation (12), the battery autonomy duration under pure battery power is calculated as:

$$T_{\text{automony}} = \frac{E_{\text{usable}}}{P_{\text{pump}}} = \frac{102.4\ \text{Wh}}{24.0\ \text{W}} = 4.27\ \text{hours} \quad (12)$$

This indicates that the prototype battery pack can continuously run the irrigation pump for approximately 4 hours and 16 minutes without any solar contribution. The variations in battery state of charge (SOC) estimated via Coulomb counting alongside core battery temperature are illustrated in Figure 6.

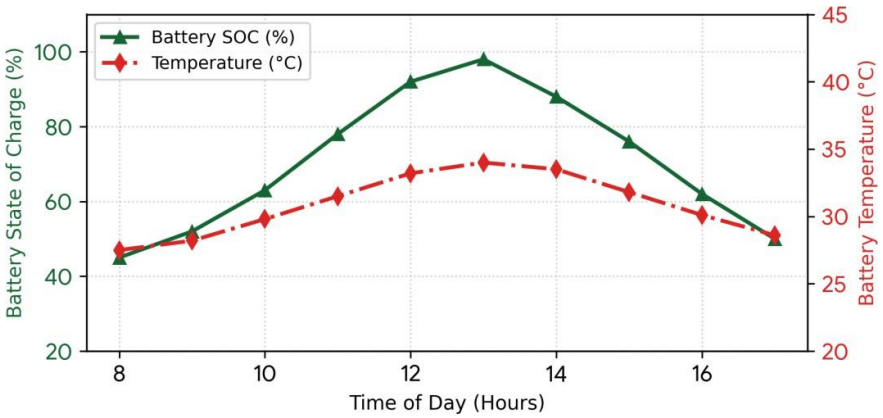


Figure 6. Battery state of charge (SOC) trend and battery temperature during testing.

3.4. Efficiency and Overall Performance Summary

The overall system and charging efficiencies were calculated based on cumulative energy transfers recorded during testing. With total PV energy generation E_{PV} = 328.2 Wh, net energy stored in the battery E_{stored} = 108.5 Wh, and total energy consumed by the pump load E_{load} = 236.0 Wh, the battery charging efficiency and overall system efficiency are evaluated using Equation (13) and Equation (14), respectively:

$$\eta_{\text{charge}} = \frac{108.5\ \text{Wh}}{328.2\ \text{Wh}} \times 100\% = 33.06\% \quad (13)$$

$$\eta_{\text{system}} = \frac{236.0\ \text{Wh}}{328.2\ \text{Wh}} \times 100\% = 71.91\% \quad (14)$$

A summary of the prototype experimental outcomes and performance metrics across the tested operational regimes is provided in Table 6.

Table 6. Experimental performance summary across tested operational conditions.

Condition	Operating Mode	PV Power (W)	Pump Power (W)	Net Battery State	System Efficiency (%)
Condition 1	High Irradiance	45.0 – 57.0	24.0	Charging (+1.2 to +2.1 A)	71.91%
Condition 2	Low Irradiance	16.8 – 18.6	24.0	Discharging (-0.4 to -0.6 A)	68.40%
Condition 3	Zero Irradiance	0.0	24.0	Discharging (-2.0 A)	88.50% (Battery to Load)
Condition 4	Variable Load	30.0 – 50.0	12.0 – 36.0	Dynamic (+0.5 to -1.2 A)	70.15%

4. Conclusions

In this study, a small-scale prototype of an IoT-based solar energy storage and monitoring system was successfully designed and empirically evaluated. The experimental data regarding the system's performance, utilising a 60 Wp PV panel, an ESP32 microcontroller, and a 4S 12.8 V $LiFePO_4$ battery pack, are presented

here in response to the research objectives. The findings demonstrate that the proposed telemetry architecture can accurately monitor real-time electrical parameters and battery state of charge (SOC) with high precision, maintaining an average sensor error below 1.2%. The prototype achieved a charging efficiency of 33.06% and an overall system efficiency of 71.91% under varying irradiance conditions. Furthermore, the 10 Ah battery capacity proved sufficient to sustain the 24 W irrigation pump for approximately 4.27 hours during zero-irradiance night-time operations. However, because the current investigation was strictly limited to a small-scale laboratory prototype, more comprehensive field experiments and long-term scaling studies are needed to verify the operational reliability of this energy distribution flow topology under continuous, heavy-load agricultural environments.

Declaration of Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper. No financial support, grants, or other forms of compensation were received that could have influenced the outcomes of this work. The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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