CHAPTER 4

DEVELOPMENT OF A REAL-TIME BATTERY MONITORING SYSTEM USING IOT AND SOLAR ENERGY FOR LOW-POWER DEVICES

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4.1 INTRODUCTION

Access to reliable electricity in rural and remote areas remains limited due to the high cost and logistical challenges of extending traditional power grids. This lack of stable power disrupts daily activities, reduces productivity, and affects access to essential services. Conventional uninterruptible power supply often relies mainly on grid charging, which results in high operational costs and limited resilience. Solar-based hybrid systems provide a sustainable alternative, yet many existing configurations lack real-time monitoring capabilities that are crucial for efficient operation and fault detection. Solar energy continues to gain widespread adoption because it is abundant and cost effective. Previous studies have examined its performance and limitations. Melveyson et al. showed that hybrid solar and wind systems improve stability during low sunlight conditions but are constrained by the absence of real-time optimization tools [1]. Alavi et al. highlighted the influence of environmental factors on solar output and the need for storage and monitoring to address fluctuations [2]. Kumar et al. reported an annual solar panel degradation rate of 0.5 percent, which reinforces the importance of regular monitoring and maintenance [3]. Farooq et al. demonstrated that grid-connected solar systems enhance energy utilization but depend strongly on efficient storage solutions [4]. These works collectively emphasize the importance of monitoring and storage systems in improving reliability.

Battery performance is a central concern in off-grid systems. Akanmu demonstrated that monitoring parameters such as state of charge, voltage, and temperature prevents overcharging and extends battery lifespan [5]. Raman et al. identified inefficiencies in charge and discharge cycles and suggested monitoring as a solution [6]. Reddy et al. showed that effective state of charge management significantly improves battery life in remote environments [7]. Li et al. examined performance differences between well-maintained and poorly maintained batteries and found rapid degradation in the absence of proper monitoring [8]. Singh et al. developed a battery management system that improved safety and performance through continuous tracking of key parameters [9]. These studies support the need for proactive battery health monitoring in hybrid solar systems.

The integration of Internet of Things (IoT) technologies has significantly improved energy management in renewable systems. Farooq et al. demonstrated that IoT enhances data visibility and reduces energy loss [4]. Reddy et al. optimized solar farms using IoT dashboards that improved energy yield and operational reliability [7]. Alhussain et al. highlighted IoT scalability for remote renewable installations [10]. Kumar et al. showed improvements in energy usage tracking when IoT is integrated with smart grid platforms [3]. Das et al. emphasized the ability of IoT systems to detect issues quickly and reduce downtime [11]. These findings show that IoT enables real-time data collection, predictive maintenance, and improved system efficiency.

Despite these advances, many solar systems used in remote and off-grid settings still lack comprehensive monitoring and control features. This limitation reduces efficiency, shortens battery lifespan, and increases the risk of unexpected failures. Addressing these challenges is important to ensure reliable and sustainable energy access.

This chapter presents the development of an IoT-enabled solar energy management system with real-time battery health monitoring. The system integrates sensors, data analytics, and a user-oriented dashboard to improve storage performance, optimize energy usage, and enhance system reliability. The work aims to provide a cost effective and sustainable solution for long-term energy access in off-grid and remote communities.

4.2 PROJECT METHODOLOGY

Figure 4.1 presents the block diagram of the Solar Powered IoT-Based Energy Management System with Real-Time Battery Health Monitoring.

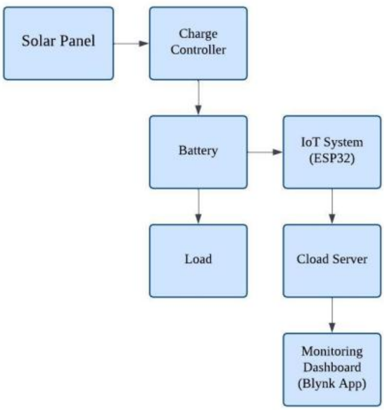

Figure 4.1: Block Diagram of the Project.

Figure 4.2 shows the flowchart of the project, which outlines the operational sequence involving the main electrical and electronic components. These include the photovoltaic system, the uninterruptible power supply, the electronic components control, and the implementation of the system's coding.

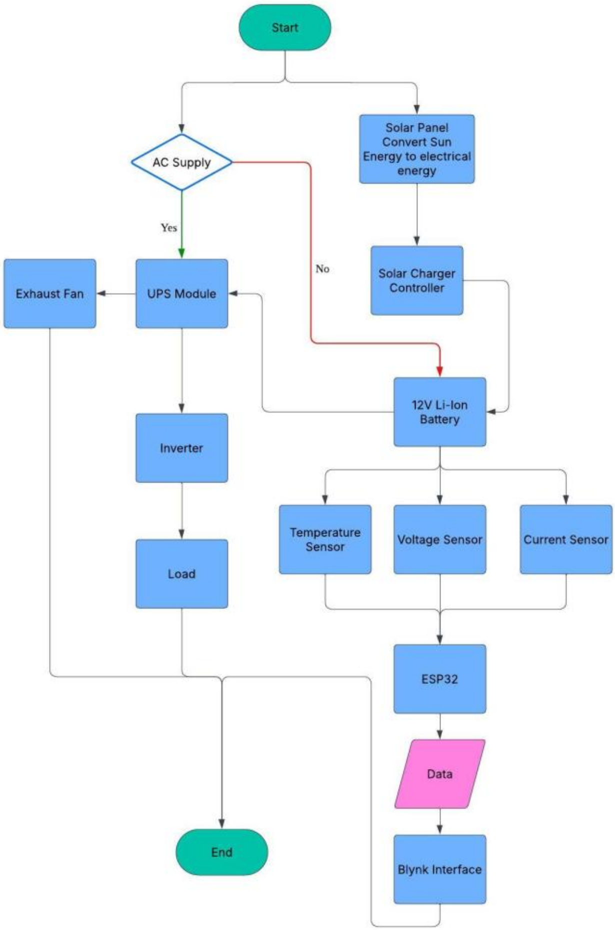

Figure 4.2: The Project Working Principal Flowchart.

This system utilizes only renewable energy generation which solar energy as its source combined with battery storage, monitoring, IoT and data visualization in ensuring an effective, uninterrupted and reliable power management for stand-alone system (off grid). This system has two flows i.e. energy flow and data flow.

On the energy flow side, the solar panel generates electricity, which is controlled by the charge controller, and then stored in the battery. The energy stored is delivered to the load accordingly. On the other hand, in the case of data flow sensors are attached to the battery and other components to acquire performance data, and the IoT system processes the gathered data to transmit it to the cloud server. Finally, the cloud server performs real-time visualization and alerts that appear on the monitoring dashboard.

The schematic diagram showing the arrangement and connections of the system is presented in Figure 4.3. As illustrated, the system is a self-contained solar-powered UPS integrated with a real-time IoT monitoring module. The system consists of a 10 W solar panel, a 12 V lead-acid battery, a 12 V/24 V 10 A solar charge controller, a 4000 W inverter, a 12 V exhaust fan, and several monitoring sensors (DS18B20, ACS712, and a voltage sensor), all interfaced with an ESP32 microcontroller. The solar battery bank is connected in parallel with the UPS input to ensure supply redundancy during low-sunlight periods or overload conditions. The ESP32 is powered directly from the DC USB output of the charge controller, enabling fully autonomous operation.

The voltage sensor monitors the battery terminal voltage, while the ACS712 sensor is placed between the battery and inverter to measure current and detect load variations in real time. The DS18B20 sensor is attached to the battery casing, where temperatures reached approximately 36 °C during testing, confirming the need for the 12 V exhaust fan to reduce heat and prevent battery degradation. Voltage, current, temperature, SoC, and battery status are transmitted via Wi-Fi to the Blynk IoT dashboard, where the data is displayed through gauges and time-based graphs for continuous monitoring.

The hardware layout follows the intended prototype design. The microcontroller and sensors are positioned near the control section, while higher-power components such as the battery, UPS kit, and inverter are grouped separately. This arrangement minimizes electrical noise and electromagnetic interference, protects the microcontroller, and simplifies wiring for maintenance. Overall, the physical integration demonstrates the successful development of a compact and intelligent solar UPS system that provides reliable power backup and real-time monitoring.

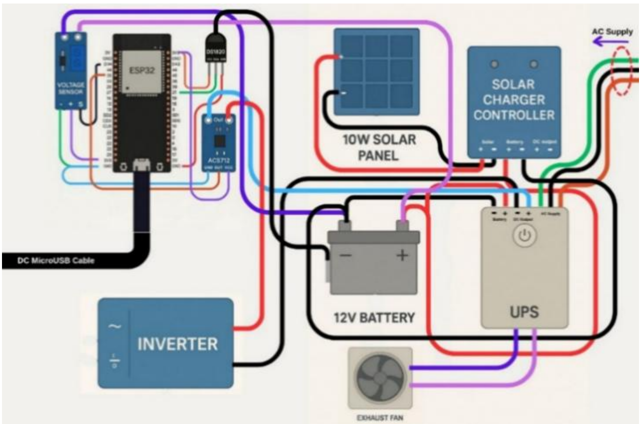

Figure 4.3: Schematic Diagram of Arrangement and Connection of the System.

4.3 RESULTS AND DISCUSSION

4.3.1 SOLAR SYSTEM ANALYSIS

Table 4.1 presents the solar system assessment conducted over seven days, from May 24 to May 30, in Parit Raja using a 10 W monocrystalline solar panel. The energy generated was estimated using the equation shown below:

$$Energy\ Output\ (Wh) = Panel\ Power\ (W) \times\ Peak\ Sun\ Hours\ (PSH)$$

Daily energy output ranged from 45.0 Wh to 49.0 Wh, with the highest value of 49.0 Wh recorded on May 27. This peak corresponded with strong voltage readings of 12.7 V, a current of 1.1 A, and a steady increase in the State of Charge (SoC) as observed on the Blynk dashboard. On May 28, the optimal panel tilt angle was identified as 45 degrees, producing 48.0 Wh with stable input current measured by the ACS712 sensor. Higher temperatures, such as the 36 °C recorded on May 30 by the DS18B20 sensor, resulted in reduced output due to decreased photovoltaic efficiency. On the bright sunny day of May 25, thermal losses were evident, as voltage remained constant despite rising temperature. Minor daily variations in current on May 29 were attributed to environmental or load changes, but output stabilization was influenced by the solar charge controller.

Overall, the combination of the ESP32, sensors, and the Blynk platform provided effective real-time monitoring. The results highlight the importance of controlling panel angle, temperature, and current to maximize the performance of small-scale off-grid solar systems.

Table 4.1: Solar Energy Output (Parit Raja).

Date	Time Window Observed)	Estimated Peak Sun Hours (PSH)	Solar Panel Power (W)	Formula Used	Estimated Energy Output (Wh)	Remarks
May 24	10:00 AM – 4:00 PM	4.5	10	10 × 4.5	45.0	Normal sunny day, data from Blynk is stable
May 25	10:00 AM – 4:00 PM	4.7	10	10 × 4.7	47.0	Slightly higher temperature noted via sensor
May 26	10:00 AM – 4:00 PM	4.6	10	10 × 4.6	46.0	Voltage output peaked at 12.7V @ 1.1A
May 27	10:00 AM – 4:00 PM	4.9	10	10 × 4.9	49.0	Blynk data showed consistent SoC rise
May 28	10:00 AM – 4:00 PM	4.8	10	10 × 4.8	48.0	Panel at 45° tilt yielded highest current
May 29	10:00 AM – 4:00 PM	4.7	10	10 × 4.7	47.0	Minor current fluctuation noted (ACS712)
May 30	10:00 AM – 4:00 PM	4.6	10	1 0× 4.6	46.0	Temperature sensor (DS18B20) logged ~36°C

4.3.2 PERFORMANCE ANALYSIS TEST UNDER DIFFERENT SCENARIOS

This section analyzes the performance of the proposed solar-powered UPS system under different test conditions in terms of solar voltage, battery voltage, UPS output, load current, solar power, battery SoC, efficiency, and response time. Table 4.2 summarizes the performance analysis under various scenarios. During bright sunny conditions, the system achieved 18 V (9 W) of solar input at 85 percent SoC with 92 percent efficiency, providing sufficient power to charge the battery and supply the load. Under overcast conditions, the solar voltage dropped to 14.2 V and power to 7.1 W, causing the battery to support the load as the SoC decreased to 78 percent. However, UPS continued to deliver stable output.

In the power outage test, which simulated a complete loss of solar input, the UPS quickly shifted to battery mode with a switching time of 12 ms. The SoC slightly decreased to 75 percent, demonstrating strong failover capability. Under high load conditions (1.2 A), the system maintained a constant output voltage of 12.31 V with an efficiency of 89 percent. The solar panel delivered up to 12 W, and the SoC stabilized at 80 percent, indicating robust load-handling performance.

When the solar input was manually disconnected, the system operated entirely on battery power, successfully passing the robustness test. During solar charging, the system reached an SoC of 82 percent with 10.6 W of solar input while supporting a low 0.6 A load, confirming proper operation of the charger and monitoring components. The switchover time test measured a 14 ms transition with no significant voltage drop, demonstrating reliable control logic and hardware integration. Finally, IoT reading verification showed that real-time data from the ESP32 and sensors closely matched manual measurements, confirming the accuracy of the monitoring system.

Table 4.2: Performance Analysis Test Under Different Scenarios.

Test Scenario	Solar Voltage (V)	Battery Voltage (V)	UPS Output Voltage (V)	Load Current (A)	Solar Power (W)	Battery SoC (%)	UPS Efficiency (%)	Response Time (ms)	System Status	Remarks
Sunny day test	18	12.5	12.31	0.5	9	85	92	15	Solar powering load	System performing well
Cloudy weather	14.2	11.8	12.30	0.5	7.1	78	90	18	Battery kicks in	Low solar power, battery active
Power outage test	0	11.6	12.29	0.5	0	75	91	12	UPS Active	UPS transitioned smoothly
High load condition	18.5	12.1	12.31	1.2	12	80	89	20	Load supported	Handled additional load well
Solar panel disconnected	0	11.5	12.28	0.4	0	70	88	25	Battery powering load	Manual disconnection tested
UPS charging from solar	17.8	12.2	12.30	0.6	10.6	82	91	10	Charging & powering load	Charging indicated, stable performance
Switchover time test	16.9	12	12.29	0.5	8.5	79	92	14	Switchover smooth	Quick UPS response

4.3.3 LOAD PERFORMANCE TEST RESULT

Table 4.3 presents a summary of the load test conducted to evaluate system performance under different load conditions for the solar-powered IoT battery system. The results show that the system maintains a stable output voltage when powering light to medium loads and provides an acceptable response under heavy loads. For loads between 0 W and 20 W, the battery voltage remained between 12.5 V and 12.6 V, indicating sufficient power availability and consistent solar charging. Under moderate loading at 60 W, where a DC exhaust fan and inverter were used, both the output voltage (12.6 V) and battery voltage (12.3 V) dropped slightly but remained within safe operating limits.

For heavy loads at 120 W, which included a fan, inverter, and phone charger, the battery voltage decreased to 12.0 V due to partial discharge as the solar panel could not fully meet the load demand. The increased current draw was successfully detected by the ACS712 sensor, and the system status was transmitted to the Blynk platform in real time for continuous monitoring. During the overload test at 150 W, the battery voltage dropped further to 11.7 V, triggering the UPS alarm and activating the under-voltage protection mechanism. This confirmed the correct operation of the system's protection features and the IoT monitoring capability, which alerts users during emergency conditions.

Overall, the system performed well under light and medium loads, and the real-time monitoring through Blynk provided clear visibility of system performance, especially as battery health and load conditions approached critical levels.

Table 4.3: Load Performance Test Result of Solar-Powered IoT-Based Battery System.

Load Type	Load Power (W)	Input Voltage (V)	Output Voltage (V)	Battery Voltage (V)	UPS Status
No Load	0	230	13.8	12.6	Normal Operation
Light Load (DC Exhaust Fan)	20	230	13.8	12.5	Normal Operation
Medium Load (DC Exhaust Fan + Inverter)	60	230	12.6	12.3	Normal Operation
Heavy Load (DC Exhaust Fan + Inverter + Normal Phone Charger)	120	230	12.4	12.0	Battery Discharging
Overload Test (DC Exhaust Fan + Inverter + 60W Phone Charger)	150	230	12.2	11.7	Alarm Triggered

4.4 CONCLUSION

In summary, this project has achieved its goal to design and develop solar powered battery monitoring system with real-time health diagnostics using IoT. The ESP32 microcontroller had related to Blynk platform for cloud purposes and sensors were successfully implemented for monitoring battery voltage, current and temperature. This active condition monitoring based system offered reliable services for remote monitoring, fault diagnostics and performance analysis of phytoremediation unit throughout stable operation by different environmental and load circumstances. It has practical applications for in the real-world where grid connections are difficult, scaling to provide more batteries in line with increased solar generation and more sophisticated analytics. Planned improvements would incorporate predictive maintenance using machine learning, enhance mobile capabilities, and provide for higher load requirements using more ruggedized hardware.

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