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Real-Time Monitoring of Solar Battery and Lamp Conditions Using Internet of Things

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ABSTRACT

Solar photovoltaic battery systems require continuous observation to prevent unnoticed voltage decline, abnormal temperature, and lamp failure. This study developed a compact Internet of Things monitoring prototype using an ESP32 microcontroller, an INA219 sensor for voltage, current, and power, an LM35 sensor for battery temperature, and a light-dependent resistor for lamp-state detection. Sensor data were shown locally on a 16x2 liquid-crystal display and transmitted through Wi-Fi to a Blynk dashboard at a five-second update interval. The study applied experimental and engineering research procedures covering hardware design, software integration, component validation, and integrated tests under off, three load, and charging conditions. The INA219 achieved average accuracies of 99.69% for voltage, 99.32% for current, and 99.49% for power, while the LM35 reached 97.08% accuracy. The light sensor correctly separated the tested off condition at 3 lux from lamp-on conditions between 230 and 2100 lux. Across all operating modes, the local display and Blynk presented consistent measurements, and negative current reliably indicated charging. The prototype therefore provides accessible real-time monitoring of battery electrical behavior, temperature, charging direction, and lamp status, although long-term data logging and field-scale validation remain necessary.

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1. INTRODUCTION

The transition from fossil energy to renewable electricity has increased the relevance of small photovoltaic systems for residential and educational applications. Indonesia has strong solar resources because of its tropical location, but the electrical output of a photovoltaic module still varies with irradiance, weather, and operating temperature [1]-[4]. In battery-based systems, these variations influence the charging process, available energy, and the ability of the battery to supply a load. A monitoring mechanism is therefore required to expose the current operating condition rather than relying on occasional manual inspection.

Internet of Things technology provides a practical framework for connecting sensors, embedded controllers, and user interfaces through the Internet. Previous studies have used IoT architectures to monitor solar panels, smart-home electrical loads, and remotely controlled photovoltaic devices [5]-[8]. The ESP32 is particularly suitable for compact monitoring prototypes because its processing, analog input, I2C communication, and Wi-Fi functions are integrated in one controller. These capabilities reduce hardware complexity while allowing measurements to be displayed locally and transmitted to a mobile dashboard.

Related research has monitored electric-bicycle batteries, rooftop photovoltaic plants, educational solar systems, electric-vehicle batteries, and off-grid photovoltaic output [9]-[13]. These studies confirm the usefulness of remote electrical monitoring, but most focus on either electrical parameters, panel performance, or application-specific battery capacity. A lightweight prototype that simultaneously observes battery voltage, current direction, power, temperature, and the physical state of a lamp can provide a more complete operational picture, especially for small systems in which a failed lamp or abnormal battery condition may otherwise remain unnoticed.

This work integrates an INA219 current and voltage monitor, an LM35 temperature sensor, and a light-dependent resistor with an ESP32, a 16x2 liquid-crystal display, and the Blynk platform. The INA219 supports digital high-side measurement and power estimation [14], while the light-dependent resistor and LM35 provide simple physical-state and thermal measurements [16], [17]. The prototype also evaluates the sign of current to distinguish battery discharge from charging. In this paper, real-time operation refers to repeated sensor acquisition, processing, local display, and network transmission at the configured update interval; historical database storage is outside the present scope.

The study has three objectives: to validate the principal sensors against reference measurements, to characterize the integrated system under off, three lamp-load, and charging conditions, and to verify consistency between the local display and the Blynk interface. The contribution is a low-cost monitoring arrangement that combines electrical, thermal, and lamp-state information in one prototype and demonstrates its behavior through controlled, repeatable operating tests.

2. METHOD

2.1. Research Design

The research combined experimental research and engineering research. The engineering component covered requirement identification, hardware design, software development, component integration, and prototype construction. The experimental component covered comparison with reference instruments and repeated integrated testing. The sequence consisted of literature review, hardware and software design, component validation, system integration, data acquisition, analysis, and conclusion. The prototype was tested at a residential location from morning to afternoon under controlled operating conditions.

2.2. System Architecture

The energy path consisted of a 20 Wp solar panel, two series-connected 18650 lithium-ion cells, and a multi-level light-emitting-diode load. The monitoring path was separated into sensing, processing, local visualization, and Internet communication. As illustrated in Figure 1, the INA219 measured bus voltage and shunt current, the LM35 measured battery temperature, and the light-dependent resistor detected the lamp illumination state. The ESP32 processed these measurements, calculated power, updated the liquid-crystal display, and transmitted the same variables to Blynk through Wi-Fi.

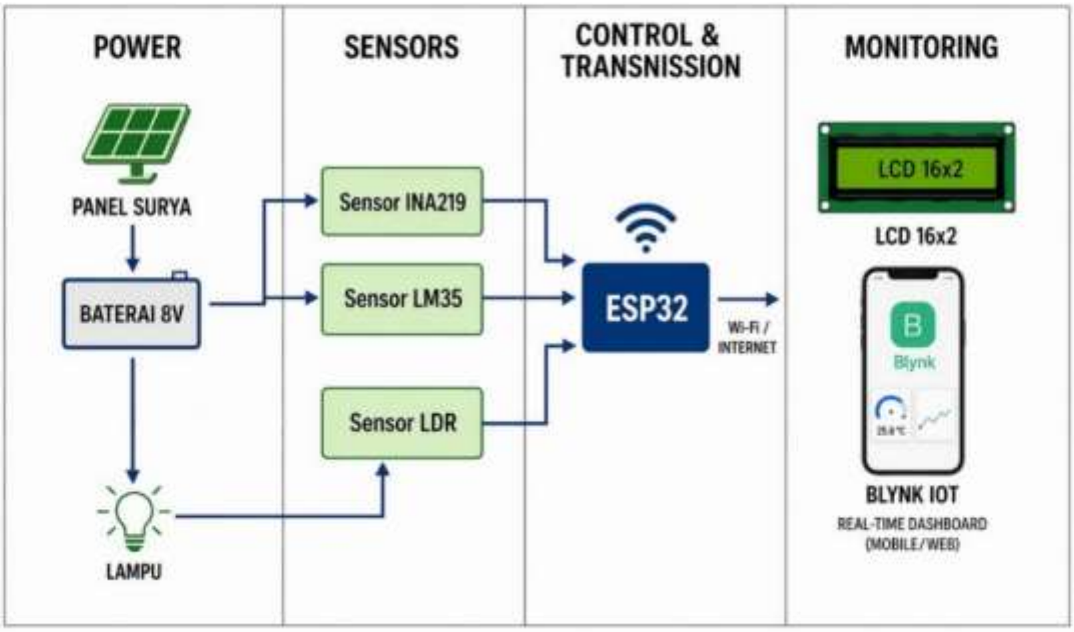

Figure 1. Functional architecture of the photovoltaic battery monitoring system

The tested prototype used the direct-charging arrangement documented in the source study, without a dedicated solar charge controller. This arrangement was used only for controlled prototype testing. It is not presented as a recommended full-scale charging architecture because long-term battery protection requires appropriate charge regulation and a battery-management strategy.

2.3. Hardware and Software Integration

Table 1. Main hardware and software elements

Element	Interface	Function
20 Wp solar panel	DC power path	Supplies charging voltage to the battery prototype
Two 18650 cells	Series connection	Stores energy and supplies the lamp load
INA219	I2C	Measures voltage and current; supports power calculation
LM35	Analog input	Measures battery-surface temperature
Light-dependent resistor	Analog/digital input	Classifies lamp illumination as on or off
ESP32	I2C, ADC, Wi-Fi	Processes sensor data and connects to the Internet
16x2 liquid-crystal display	I2C	Displays measurements locally
Blynk application	Wi-Fi/cloud	Displays remote measurements and operating status

The ESP32 firmware was developed in the Arduino integrated development environment using C/C++. During initialization, the program configured input and output pins, started the I2C bus, initialized the INA219 and display, and connected to Wi-Fi and the Blynk server. The main loop read all sensors, converted the LM35 voltage to temperature, classified the lamp state, calculated power, identified charging or discharging from current direction, and sent the output to both interfaces. Reconnection logic was included so that local monitoring could continue and the network link could recover after interruption. Figure 2 shows the complete electrical interconnection used in the prototype.

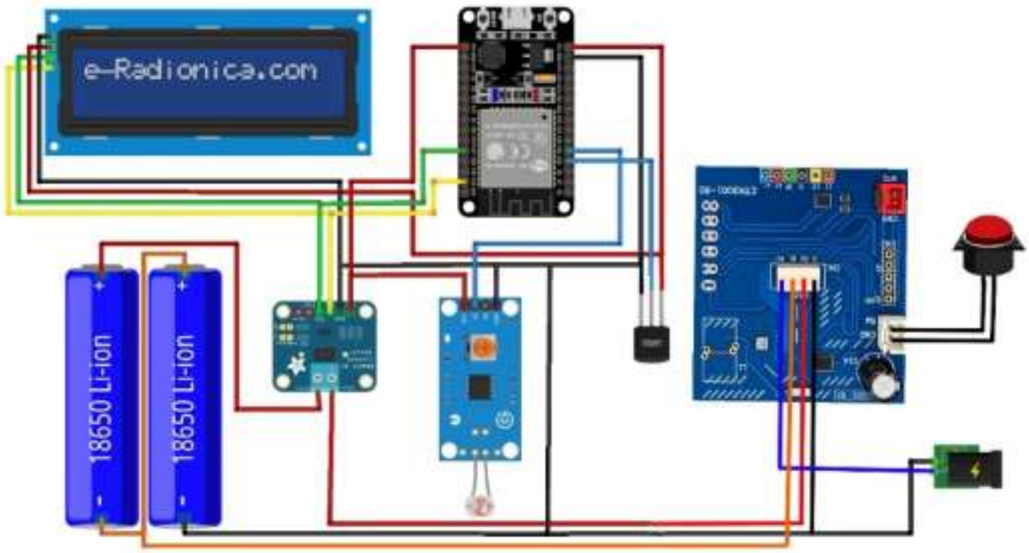

Figure 2. Overall hardware interconnection of the prototype

2.4. Test Procedure and Data Analysis

Component tests were conducted before integrated testing. Solar-panel voltage was observed during sunny and cloudy conditions. INA219 measurements were compared with an AVO meter under off and three load levels. LM35 measurements were compared with a reference thermometer at five temperatures. The light-dependent resistor was evaluated at five illumination levels measured with a smartphone lux-meter application. The ESP32, display, lamp, and Blynk communication were also tested functionally.

$$P = V \times I \quad (1)$$

where P is electrical power in watts, V is voltage in volts, and I is current in amperes.

$$Error\ (\%) = |Sensor\ value - Reference\ value|\ /\ Reference\ value \times 100 \quad (2)$$

$$Accuracy\ (\%) = 100 - Error\ (\%) \quad (3)$$

The integrated system was tested in five states: off, Mode 1 (highest lamp load), Mode 2 (medium load), Mode 3 (lowest load), and charging. Three observations were recorded for each state at five-minute intervals. The variables were voltage, current, power, temperature, lamp status, charging status, and estimated battery percentage. Data displayed on the liquid-crystal display were compared with Blynk values, while communication delay was tested three times using the programmed five-second update interval.

3. RESULTS AND DISCUSSION

3.1. Component Validation

The solar panel produced 22.1 V during sunny conditions and 18.9 V during cloudy conditions, confirming the expected effect of available irradiance on panel output. The most important component-validation results are summarized in Table 2. The INA219 showed small deviations from the AVO meter across the tested load states. Its average accuracy was above 99% for voltage, current, and power, supporting its suitability for low-voltage direct-current monitoring. The LM35 also produced measurements close to the reference thermometer, although its average error was higher than that of the digital INA219 because it depended on analog conversion, sensor placement, and thermal contact.

Table 2. Summary of component validation results

Test item	Reference or range	Main result	Interpretation
Solar panel	Sunny and cloudy	22.1 V and 18.9 V	Output changed with weather condition
INA219 voltage	AVO meter	0.31% mean error; 99.69% accuracy	High agreement with reference
INA219 current	AVO meter	0.68% mean error; 99.32% accuracy	High agreement with reference
INA219 power	Calculated/reference power	0.51% mean error; 99.49% accuracy	Suitable for prototype power monitoring
LM35 temperature	Reference thermometer	2.92% mean error; 97.08% accuracy	Acceptable for supporting thermal observation
Light sensor	3-2100 lux	3 lux = off; 230-2100 lux = on	Correct separation in the tested range
Blynk transfer	Three transmissions	5 s delay in all trials	Matched the programmed update interval

The light sensor produced logic 0 at 3 lux and logic 1 between 230 and 2100 lux. Thus, the experimental mapping used in this manuscript defines the dark condition as lamp off and the brighter conditions as lamp on. This result supports the use of a light-dependent resistor as a simple independent confirmation of the physical lamp state rather than relying only on the electrical command. Similar light-sensitive monitoring has been used in photovoltaic educational systems and automatic-light applications [11], [16].

3.2. Integrated Operating Performance

Table 3 presents averages recalculated directly from the three observations reported for each operating state. In the off state, current was effectively zero and the remaining 0.01 W reading represented minimum circuit consumption or sensor resolution. Mode 1 produced the highest average current and power because it applied the largest lamp load. The values decreased progressively in Modes 2 and 3, demonstrating that the monitoring system tracked the intended load hierarchy. During charging, current became negative, while voltage and battery percentage increased. The current sign therefore provided a useful and immediate indication of energy-flow direction.

Table 3. Average performance under integrated operating states

State	Voltage (V)	Current (A)	Power (W)	Temperature (C)	Battery (%)	Energy status
Off	8.20	0.000	0.010	31.60	93	Standby
Mode 1	8.10	0.370	3.007	33.07	92	Discharge
Mode 2	8.10	0.203	1.650	33.23	91	Discharge
Mode 3	8.10	0.060	0.490	34.33	90	Discharge
Charging	8.50	-0.060	0.513	36.10	91	Charging

The power values were also checked against Equation (1). As shown in Table 4, the measured values for the three load modes and the charging state were very close to the products of the corresponding average voltage and current magnitude. The minor differences were attributable to rounding and sensor resolution. This consistency agrees with prior findings that calibrated INA219-based systems can provide reliable direct-current electrical measurements [14], [15].

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Table 4. Comparison of monitored and calculated power

State	Average V (V)	Average |I| (A)	Calculated V x I (W)	Monitored power (W)	Absolute difference (W)
Off	8.20	0.000	0.000	0.010	0.010
Mode 1	8.10	0.370	2.997	3.007	0.010
Mode 2	8.10	0.203	1.647	1.650	0.003
Mode 3	8.10	0.060	0.486	0.490	0.004
Charging	8.50	0.060	0.510	0.513	0.003

3.3. Local and Remote Monitoring Consistency

The liquid-crystal display and Blynk showed the same voltage, current, power, lamp status, and charging status in the recorded tests. Temperature values differed only in display resolution because the liquid-crystal display used rounded whole degrees while Blynk retained decimal values. The three communication trials each produced a five-second delay, which was equal to the programmed transmission interval rather than an uncontrolled network lag. Consequently, the prototype provided predictable periodic monitoring rather than instantaneous hard real-time control.

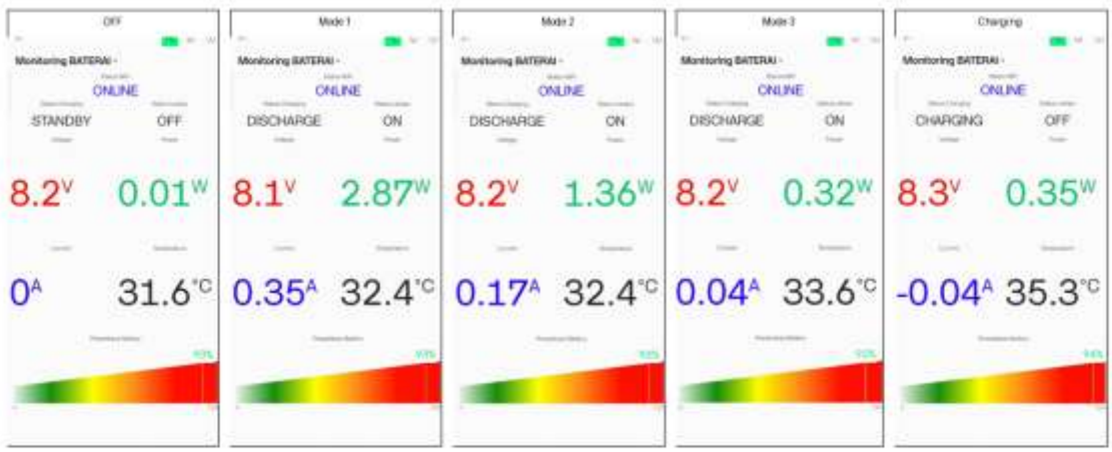

Figure 3. Blynk monitoring displays for off, load, and charging states

Figure 3 illustrates that the interface differentiated standby, discharge, and charging conditions and simultaneously exposed electrical and thermal values. In Mode 1, the dashboard showed the greatest power demand; Modes 2 and 3 displayed successively smaller demand; and the charging screen displayed negative current. This behavior is consistent with earlier IoT-based solar and battery monitoring systems that reported stable cloud visualization and remote access [10], [12], [13]. The present prototype extends that practical monitoring pattern by adding lamp-state verification and battery-surface temperature to the same interface.

3.4. Comparison with Previous Monitoring Systems

Table 5 positions the prototype against representative systems cited in the source study. The comparison does not indicate that one sensor architecture is universally superior; each design reflects its application, voltage level, and monitoring objective. Electric-bicycle and electric-vehicle studies emphasized mobility and battery capacity [9], [12], rooftop and off-grid studies emphasized photovoltaic electrical performance [2], [10], and the EduSolar system emphasized learning-oriented visualization [11]. The present work is narrower in scale but combines four operational dimensions in one interface: electrical measurement, thermal observation, physical lamp-state verification, and charging-direction identification.

Table 5. Functional comparison with representative related systems

Study	Application	Main sensing	Interface	Distinct focus
Irfan et al. [9]	Electric bicycle	Current, voltage, temperature, GPS	Arduino Cloud	Battery and vehicle physical parameters
Badruzzaman et al. [10]	Rooftop photovoltaic	PZEM-017 and PZEM-016	Blynk	Electrical monitoring with cooling system
Waluyo et al. [11]	Educational photovoltaic	ACS712, voltage, PZEM-004T, LDR	Website	Learning-oriented solar monitoring
Lianda et al. [12]	Electric vehicle	ADS1015	Blynk	Battery-capacity monitoring
Zurifqyaldi et al. [2]	Off-grid photovoltaic	PZEM-017 and PZEM-004T	IoT dashboard	DC and AC electrical parameters

Study	Application	Main sensing	Interface	Distinct focus
This work	Solar battery and lamp	INA219, LM35, LDR	LCD and Blynk	Electrical, thermal, lamp state, current direction

The practical value of this integration is diagnostic context. A power reading alone cannot confirm that the lamp is physically illuminated, and a lamp-on indication alone cannot show battery stress or charging direction. Combining these signals allows the user to interpret whether the load command produced visible output, whether the electrical demand matched the selected mode, and whether battery temperature changed during discharge or charging. The dual local-and-cloud interface also preserves immediate on-site visibility when remote access is unnecessary while retaining remote supervision when Wi-Fi is available.

3.5. Technical Implications and Limitations

The results demonstrate that low-cost sensing can expose the operating state of a small photovoltaic battery system with sufficient clarity for supervision and educational use. The strongest evidence is not a single accuracy value, but the coherence among measurements: higher load modes produced higher current and power, charging produced negative current and increasing voltage, the light sensor followed the visible lamp state, and both user interfaces reported the same system condition. This internal consistency indicates that sensor acquisition, processing, and communication operated as an integrated chain rather than as isolated component tests.

Several limitations restrict generalization. First, the prototype was evaluated on a small battery and lamp system, not on a field-scale photovoltaic installation. Second, the test duration and three observations per state were adequate for functional validation but not for long-term reliability analysis. Third, the Blynk implementation did not store historical data in a dedicated database. Fourth, illumination was measured with a smartphone application rather than a calibrated photometer. Finally, the direct-charging configuration lacked a dedicated solar charge controller; future implementations should include regulated charging, battery protection, and state-of-charge estimation appropriate to the selected lithium-ion chemistry [18]-[20].

4. CONCLUSION

A real-time Internet of Things prototype for monitoring a photovoltaic battery and lamp condition was successfully implemented using an ESP32, INA219, LM35, light-dependent resistor, 16x2 liquid-crystal display, and Blynk. The INA219 achieved average accuracies of 99.69% for voltage, 99.32% for current, and 99.49% for power, while the LM35 achieved 97.08% accuracy. The light sensor separated the tested off and on illumination conditions, and the system correctly distinguished standby, discharge, and charging through load behavior and current direction. Triplicate integrated tests showed coherent voltage, current, power, temperature, and battery trends, with consistent values on local and remote displays and a controlled five-second update interval. The prototype is therefore suitable as a practical monitoring and learning platform. Further work should add a solar charge controller, robust battery-management functions, calibrated illumination measurement, cloud data logging, alarm thresholds, and longer field testing.

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