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Solar-Powered Smart Shelter with QR Code Access Control

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Abstract

The increasing demand for sustainable public infrastructure emphasizes the importance of efficient off-grid energy solutions, especially for outdoor public shelters. In Malaysia, such shelters generally offer basic electrical amenities like lighting, ventilation, and charging ports, but most lack integrated monitoring and energy management systems. This project details the design, implementation, and experimental testing of a solar-powered smart shelter equipped with Internet of Things (IoT) monitoring and QR code–based access control to enhance energy efficiency and operational dependability. The system features a standalone photovoltaic setup with a 50 W monocrystalline solar panel, a PWM charge controller, and a 12 V battery to supply direct current loads. Two ESP32 microcontrollers facilitate real-time energy monitoring, load management, and user interaction via a web interface. Experimental trials over three days under actual environmental conditions showed the system operated reliably. Peak solar current reached 2.7 A during periods of high irradiance, with battery voltage staying within 12.15 V and 13.58 V. The highest load recorded was 9.57 W, and the voltage remained stable throughout testing. These findings validate the system's practicality and reliability for sustainable off-grid public shelter use.

1. Introduction

The global move toward cleaner energy sources has sped up the adoption of renewable technologies to cut down pollution, carbon emissions, and reliance on fossil fuels. Solar energy is a dependable renewable resource, especially in areas with consistent sunlight year-round. Malaysia's location on the equator results in high daily solar irradiation, making solar photovoltaic systems a good choice for electricity generation. Still, managing energy effectively remains a challenge, particularly for small-scale public infrastructure.

In recent years, the Internet of Things (IoT) has dramatically transformed how energy systems are monitored and managed. By enabling real-time control and connectivity between devices, IoT boosts energy efficiency, safety, and convenience [1]. This idea has expanded to include the Smart Built Environment (SBE), where interconnected sensors and controllers work together to optimize energy use and enhance comfort [2]. An example of this progress is the smart shelter project in Seongdong District, South Korea, which uses IoT and ICT technologies to provide real-time information, wireless charging, and smart safety features. These innovations improve safety, comfort, and energy efficiency for the public [3].

Public shelters are vital parts of Malaysia's urban infrastructure, offering basic electrical amenities like lighting, ventilation fans, and USB charging ports. However, most shelters lack integrated monitoring systems and controlled access, leading to inefficient energy use and limited visibility into operations. The absence of real-time monitoring and smart controls is a common shortcoming of traditional infrastructure, which hampers performance optimization [4], while increased usage further highlights inefficiencies in current operations [5].

Without integrated monitoring and energy management systems, public facilities often waste energy and do not operate at optimal levels. This underscores the need for better control and visibility of energy consumption to minimize waste and improve reliability [6]. Combining IoT technology with alternative energy sources enables continuous monitoring and control of energy performance, which is crucial for sustainable energy management [7]. Therefore, this project aims to develop a solar-powered smart shelter with IoT-based monitoring and QR code-controlled access, focusing on system design and implementation of the smart shelter system, real-time monitoring and control, and evaluating the system's performance through experiments.

2. Literature Review

Solar photovoltaic (PV) systems are commonly employed as a sustainable energy solution for off-grid and public infrastructure applications. A stand-alone PV system typically consists of PV modules, a charge controller, an inverter, an energy storage system such as a battery, and an electrical load [8]. These systems are especially advantageous in remote and rural areas where the connection to the grid is minimal or nonexistent. They provide a reliable and sustainable power source, making them ideal for use in smart shelters, emergency communication centers, or isolated households [9]. Nonetheless, the performance of these systems can be influenced by environmental and design factors, including solar irradiance, temperature, panel orientation, shading, and dust buildup [10] [11]. Fig 1 shows environmental factor affecting solar PV output.

Fig. 1 *Environmental Factors Affecting Solar PV Output [11]*

Malaysia's tropical climate offers favorable conditions for solar energy deployment, with average daily solar irradiation ranging from 4.21 kWh/m^2/day to 5.56 kWh/m^2/day [12] [13]. However, seasonal monsoon variations do affect PV performance. This cyclical fluctuation directly impacts the energy output of solar PV systems, leading to significant declines during the monsoon months due to reduced solar radiation and more scattered sunlight [14]. These factors underscore the critical need for effective energy management and monitoring to maintain reliable system operation.

The incorporation of Internet of Things (IoT) technology has improved automation, monitoring, and energy efficiency in smart shelters. Other research demonstrated that IoT-enabled smart shelters with automated cooling systems could reduce energy consumption by up to 80%, while simultaneously enhancing user comfort. IoT-based environmental control systems allow for adaptive responses to real-time conditions, thereby increasing operational efficiency [15]. As shown in Fig 2, urban cooling shelters equipped with IoT sensors can automatically modify misting and ventilation systems based on temperature and humidity levels, optimizing comfort and reducing energy use [15].

Fig. 2 *Left photo shows the PV-powered misting system with battery storage, while the right photo shows the monitoring system in operation [15]*

Despite recent advancements, many IoT-based shelter systems still depend significantly on full automation or mobile applications, which can restrict accessibility and user engagement in shared public settings. QR code technology has emerged as a straightforward and accessible interface for IoT control. Furthermore, a QR-based IoT control system allows users to turn a light ON or OFF simply by scanning a QR code linked to a web platform [16]. In this project, combining IoT and QR technologies enables users to scan a QR code placed in the solar-powered smart shelter to operate the DC fan, lamp, and USB charging port through an online interface. This feature not only enhances convenience and accessibility but also encourages efficient energy use, demonstrating how smart automation can support sustainable, solar-powered public infrastructure. Therefore, there remains a need for a solar-powered smart shelter that integrates renewable energy, IoT-based monitoring, and an accessible QR-based control mechanism suitable for public environments.

3. Methodology

This section details the methodology employed in the development and assessment of the solar-powered smart shelter system. It covers the overall system architecture, hardware and software implementation, control and monitoring framework, and the testing procedures used to verify functionality and performance. The approach was designed to ensure reliable operation, efficient energy management, and practical deployment in outdoor environments.

3.1 Block Diagram of the System

The block diagram depicts the overall design of the solar-powered smart shelter system. This system comprises a 50W monocrystalline solar panel, a PWM solar charge controller, and a 12V sealed lead-acid battery that together serve as the off-grid power source. Two ESP32 microcontrollers are utilized: one manages user access and load control, while the other is responsible for monitoring electrical parameters. Relay modules control various DC loads, such as a 12V LED lamp, a 5V fan, and USB charging ports. Environmental sensing is carried out using a PIR motion sensor and a GL55 LDR photoresistor. Additionally, system voltage and load current are measured with DC voltage sensors and ACS712 current sensors. The data collected are transmitted to the Blynk IoT platform for real-time monitoring. Fig 3 shows the block diagram of the project.

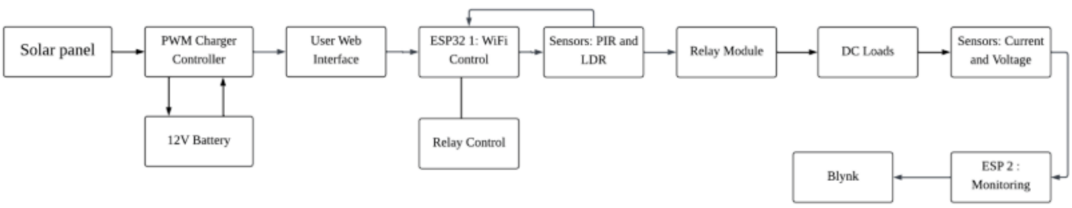
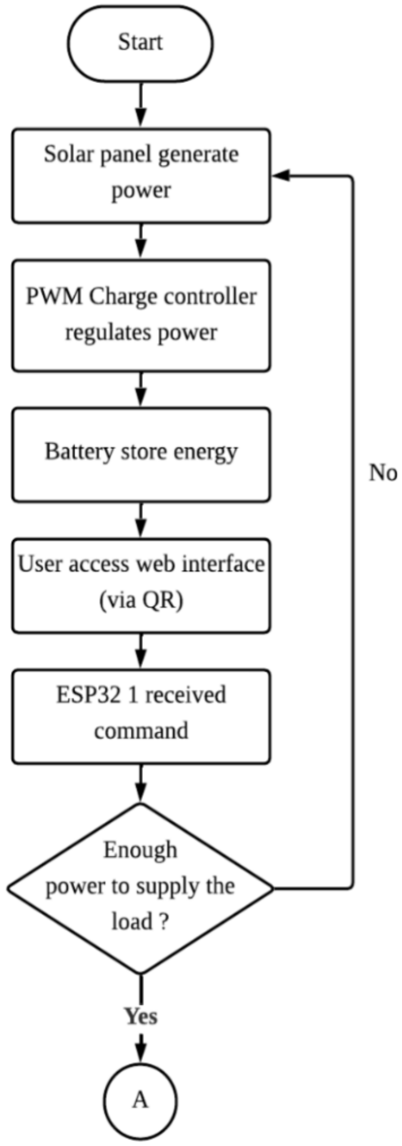


Fig. 3 *Block Diagram of the project*

3.2 System Flowchart

The system flowchart outlines the operational logic of the smart shelter. Solar energy is captured by the photovoltaic panel and regulated by the PWM charge controller before being stored in the 12V battery. User access is initiated through a QR code linked to a web interface managed by the first ESP32. The system verifies the battery's availability prior to allowing load activation. Automated control is achieved using the PIR sensor for occupancy detection and the LDR sensor for light-based lamp operation. When no motion is detected within a predefined period, all loads are automatically turned off to conserve energy. Real-time voltage, current, and power data are continuously collected by the second ESP32 and transmitted to the Blynk platform for monitoring. Fig 4 shows system flowchart.



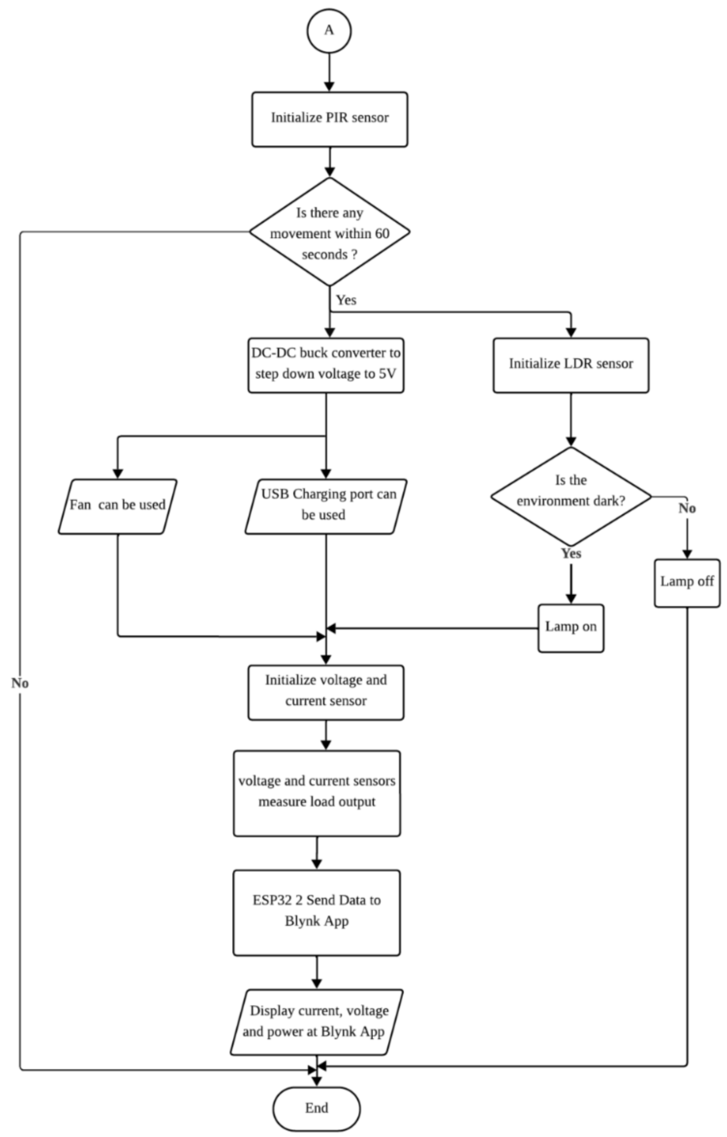


Fig. 4 *System Flowchart*

3.3 Schematic Diagram and Hardware Integration

The schematic diagram depicted in Figure 5 illustrates the electrical connections among all system components. The solar panel, charge controller, battery, sensors, relay module, DC-DC buck converter, and ESP32 microcontrollers were interconnected to guarantee stable power distribution and safe operation. The XL1509 step-down module was employed to transform the 12V supply into a regulated 5V output for the fan and USB ports. Status indication was achieved through LED and buzzer modules managed by the initial ESP32. All electronic components were housed within a dedicated system box, as shown in Figure 6, to protect the circuitry and keep wiring organized. This hardware integration supported reliable load switching, sensor operation, and continuous system monitoring.

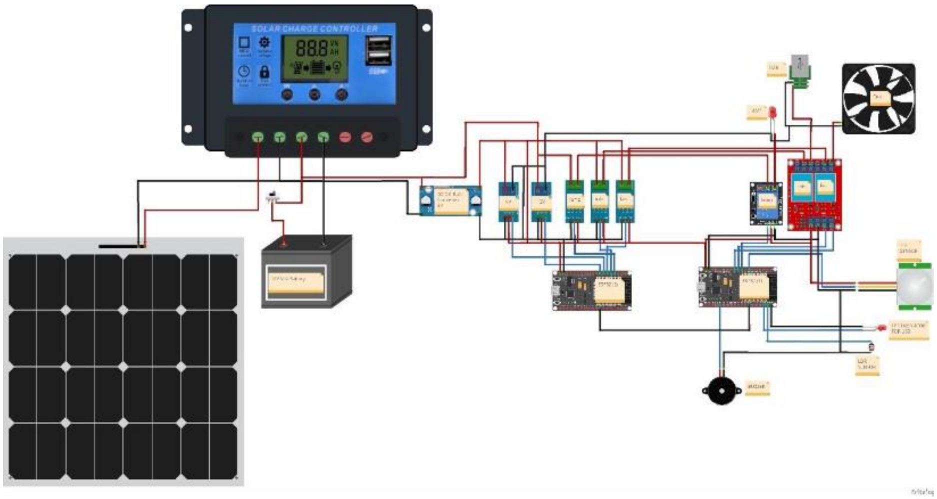


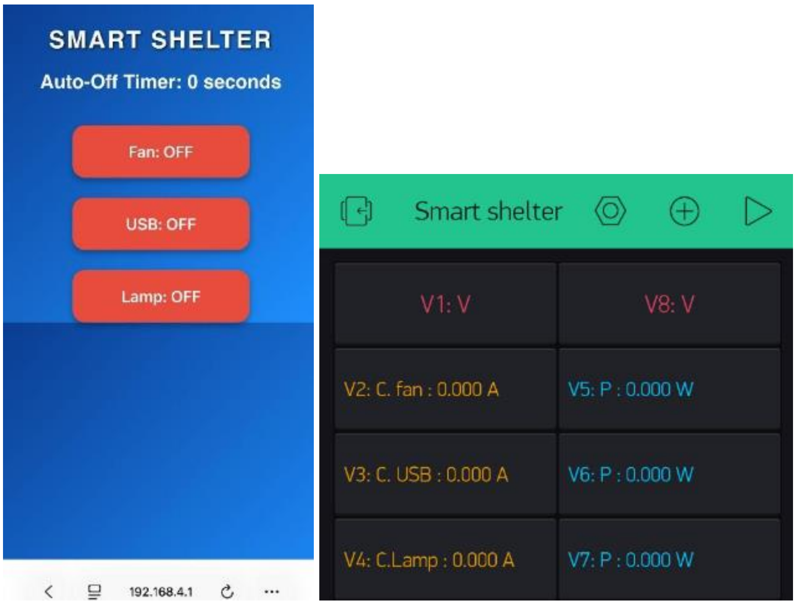
Fig. 5 *Schematic diagram of the project*

(a) **(b)**

Fig. 6 *(a) Internal Wiring and the Dual-ESP32 Setup, (b) External View of the System Box*

3.4 Software Implementation

The control and monitoring software was created using the Arduino Integrated Development Environment. The first ESP32 carried out control logic for QR code authentication, relay switching, and sensor-based automation, while the second ESP32 was responsible for collecting data from voltage and current sensors. Electrical parameters such as supply voltage, load current, and power consumption were sent to the Blynk application for real-time visualization. This software setup allowed for coordinated interaction between user commands, automated responses, and monitoring functions. Fig 7 displays the software system which includes (a) the QR code web control interface and (b) the Blynk dashboard.



(a) **(b)**

Fig. 7 *Software Interface: (a) QR Code Web Control Interface and (b) Blynk Dashboard*

3.5 QR Code Implementation

The QR code in this project functions as an IoT-based access system, enabling users to efficiently and conveniently control the loads. Before scanning, users must enable WiFi and connect to the network associated with the ESP module. Once connected, scanning the QR code redirects them to the website interface, where they can turn the load ON or OFF. To prevent unauthorized access, security measures include WiFi authentication, ensuring only connected users can operate the system. This security layer is crucial for public deployment, protecting the device from misuse. Overall, the QR code implementation enhances the IoT system's functionality by providing seamless, secure, and user-friendly remote control of the loads. Fig. 8 shows the QR Code and instruction on how to control the loads.

Fig. 8 *QR-Code Implementation*

4. Results and Discussion

This section shares the results and insights from three days of real-world testing of the solar-powered smart shelter system. It highlights how the system generates solar energy, charges its batteries, and monitors power usage through IoT in actual environmental conditions. The findings show that the system runs reliably, uses energy efficiently, and effectively manages load control through smart technology.

4.1 Prototype Implementation and System Operation

A physical prototype of the solar-powered smart shelter system was created and deployed at a public shelter within the college residential area of Universiti Tun Hussein Onn Malaysia, Pagoh campus, to assess its performance under real operating conditions. A 50 W monocrystalline solar panel was mounted on the shelter roof at a 26° tilt angle to optimize solar energy collection, with the generated power managed by a solar charge controller and stored in a 12 V sealed lead-acid battery. All major system components, including the ESP32 microcontrollers, relay modules, voltage and current sensors, and USB charging ports, were integrated within a system box mounted on a wooden support structure. The DC loads, comprising a 12 V LED lamp and a 5 V DC fan, were installed inside the shelter and controlled via a QR code–based web interface. Real-time monitoring of voltage, current, and power consumption was carried out using the Blynk IoT platform. The successful installation and consistent operation of the prototype demonstrate the practicality and reliability of the proposed smart shelter system in real-world settings. Fig 8 illustrates the actual prototype setup at the shelter, showing (a) internal and (b) external views.

(a) (b)

Fig. 8 *Actual prototype setup (a) Internal View and (b) External View*

4.2 Solar Panel and Battery Performance

The performance of the solar panel and battery was assessed over three consecutive days under natural environmental conditions. Measurements of solar panel voltage, solar panel current, battery voltage, and solar irradiance were recorded at two-hour intervals, as outlined in Tables 1, 2, and 3. The findings indicate that solar voltage ranged from 10.2 V to 14.7 V, while solar current varied considerably depending on sunlight availability, with values as low as 0.01 A during early morning hours and reaching up to 2.50 A during periods of high irradiance.

Table 1 Solar Output and Battery Performance (Day 1)

Time	Solar Irradiance (W/m^2)	Solar Voltage (V)	Solar Current (A)	Battery Voltage (V)
8.00	42	10.50	0.02	12.81
10.00	87	11.80	0.08	12.85
12.00	153	12.50	0.25	12.92
14.00	354	13.64	0.97	13.05
16.00	421	14.00	1.22	13.1
18.00	73	12.10	0.05	12.98

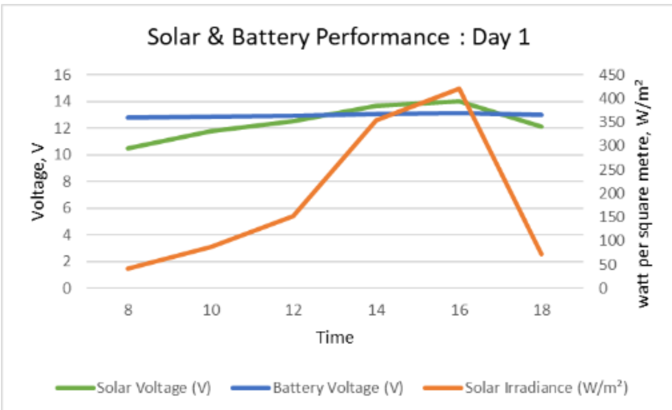
Table 2 Solar Output and Battery Performance (Day 2)

Time	Solar Irradiance (W/m^2)	Solar Voltage (V)	Solar Current (A)	Battery Voltage (V)
8.00	38	10.20	0.01	12.88
10.00	233	12.90	0.64	13.02
12.00	587	14.17	2.15	13.15
14.00	652	14.25	2.20	13.24
16.00	314	13.5	0.85	13.18
18.00	66	11.5	0.04	13.05

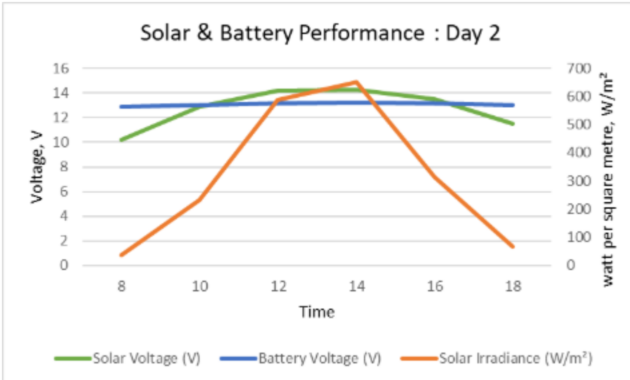
Table 3 Solar Output and Battery Performance (Day 3)

Time	Solar Irradiance (W/m^2)	Solar Voltage (V)	Solar Current (A)	Battery Voltage (V)
8.00	54	11.00	0.03	13.04
10.00	187	12.80	0.40	13.21
12.00	458	13.90	1.10	13.38
14.00	856	14.70	2.50	13.58
16.00	453	14.47	1.40	13.44
18.00	221	14.15	1.15	13.30

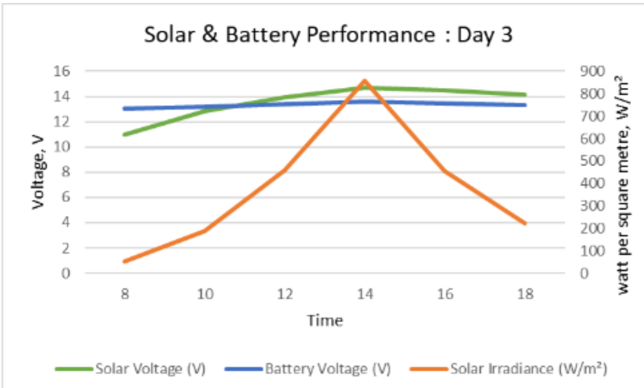
The battery voltage remained relatively steady during the testing period, fluctuating between 12.81 V and 13.58 V, which demonstrates effective charge regulation and energy storage. The highest solar current and irradiance were recorded on Day 3 at 2:00 PM, with a peak irradiance of 856 W/m^2. In comparison, lower current readings on Days 1 and 2 were caused by cloudy and rainy weather conditions. Fig 9 further illustrates the relationship between solar irradiance, solar voltage, and battery voltage, indicating that despite varying weather conditions, the system consistently maintained battery charging performance, confirming the adequacy of the solar panel and charge controller setup.



(a)



(b)



(c)

Fig. 9 *Solar and Battery Performance Analysis for: (a) Day 1, (b) Day 2 and (c) Day 3*

4.3 IoT Monitoring and Load Consumption

The load consumption and monitoring performance of the smart shelter system were evaluated through IoT-based measurements collected via the Blynk platform. Three DC loads were monitored: a 12 V LED lamp, a 5 V DC fan, and a 5 V USB charging port. The quantities of voltage, current, and power consumption for each load over a period of three days are shown in Tables 4, 5, and 6. The supply voltage remained stable across all loads, with the 5 V loads operating within the range of 4.13 V to 5.28 V, and the 12 V LED lamp operating between 12.27 V and 13.58 V.

Table 4 IoT Monitoring and Load Consumption (Day 1)

Time	Fan (V)	Fan (A)	Fan (W)	USB (V)	USB (A)	USB (W)	Lamp (V)	Lamp (A)	Lamp (W)	Total Load (W)
10.00	5.28	0.00	0.00	5.28	0.00	0.00	12.85	0.00	0.00	0.00
12.00	4.56	0.00	0.00	4.56	1.25	5.70	12.92	0.00	0.00	5.70
14.00	4.43	0.00	0.00	4.43	1.34	5.94	13.05	0.00	0.00	5.94
16.00	4.77	0.00	0.00	4.77	0.00	0.00	13.10	0.00	0.00	0.00

18.00	4.23	0.00	0.00	4.23	0.00	0.00	12.98	0.00	0.00	0.00
20.00	4.17	0.00	0.00	4.17	0.00	0.00	12.80	0.35	4.48	4.48
22.00	4.17	0.00	0.00	4.17	0.00	0.00	12.75	0.34	4.33	4.33
Average	**4.52**	**0.00**	**0.00**	**4.52**	**0.37**	**1.66**	**12.92**	**0.10**	**1.26**	**2.92**

Table 5 IoT Monitoring and Load Consumption (Day 2)

Time	Fan (V)	Fan (A)	Fan (W)	USB (V)	USB (A)	USB (W)	Lamp (V)	Lamp (A)	Lamp (W)	Total Load (W)
10.00	4.13	0.00	0.00	4.13	0.00	0.00	13.02	0.00	0.00	0.00
12.00	4.97	0.00	0.00	4.97	0.00	0.00	13.15	0.00	0.00	0.00
14.00	4.93	0.00	0.00	4.93	1.17	5.77	13.24	0.00	0.00	5.77
16.00	5.24	0.00	0.00	5.24	0.85	4.45	13.18	0.00	0.00	4.45
18.00	4.34	0.00	0.00	4.34	0.00	0.00	13.05	0.00	0.00	0.00
20.00	4.78	0.00	0.00	4.78	0.57	2.72	12.95	0.37	4.79	7.51
22.00	4.43	0.80	3.54	4.43	0.00	0.00	12.86	0.42	5.38	8.92
Average	**4.69**	**0.11**	**0.51**	**4.69**	**0.37**	**1.85**	**13.06**	**0.11**	**1.45**	**3.81**

Table 6 IoT Monitoring and Load Consumption (Day 3)

Time	Fan (V)	Fan (A)	Fan (W)	USB (V)	USB (A)	USB (W)	Lamp (V)	Lamp (A)	Lamp (W)	Total Load (W)
10.00	4.62	0.00	0.00	4.62	0.00	0.00	13.21	0.00	0.00	0.00
12.00	4.97	0.86	4.27	4.97	0.00	0.00	13.38	0.00	0.00	4.27
14.00	4.93	0.76	3.75	4.93	1.18	5.82	13.58	0.00	0.00	9.57

16.00	5.24	0.83	4.35	5.24	0.00	0.00	13.44	0.00	0.00	4.35
18.00	4.62	0.00	0.00	4.62	0.00	0.00	13.30	0.00	0.00	0.00
20.00	4.63	0.00	0.00	4.63	0.00	0.00	13.17	0.39	5.11	5.11
22.00	4.25	0.76	3.25	4.25	0.47	2.01	12.27	0.35	4.27	9.53
Average	**4.75**	**0.46**	**2.23**	**4.75**	**0.24**	**1.12**	**13.19**	**0.11**	**1.34**	**4.69**

When active, the DC fan consumed between 3.25 W and 4.35 W, while the USB charging port consumed between 2.01 W and 5.94 W during peak usage periods. The LED lamp operated exclusively during nighttime hours, drawing power between 3.89 W and 5.38 W, as controlled by the LDR sensor. The total load power varied according to user activity and sensor input, reaching a maximum of 9.57 W on Day 3, while the system maintained stable voltage performance throughout operation. Fig 10 and 11 illustrate the average and instantaneous power consumption trends, respectively, highlighting effective load management, automated control, and stable system performance throughout the monitoring period.

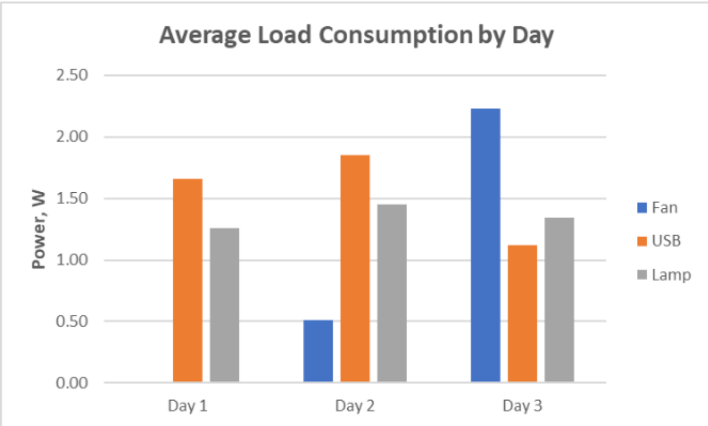


Fig. 10 *Average power consumption for each load type*

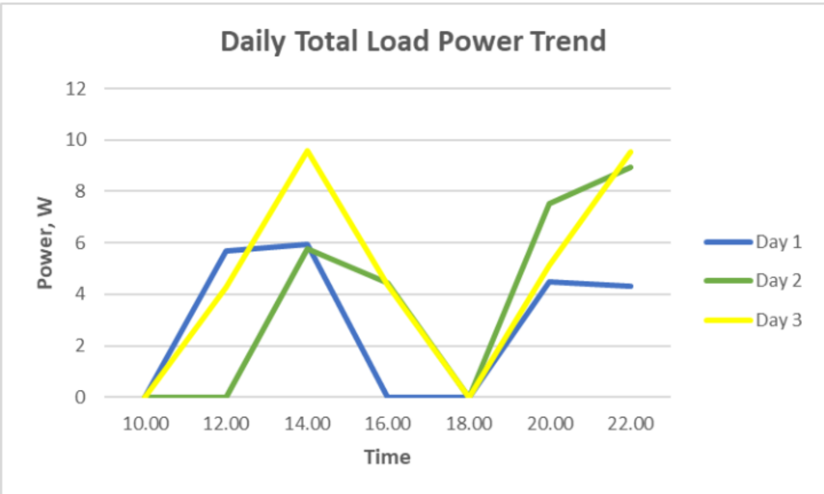


Fig 11 *Total load power Profiles for Day 1, Day 2, and Day 3*

5. Conclusion

The solar-powered smart shelter system was successfully designed, built, and tested, proving effective in combining solar energy generation, battery storage, IoT monitoring, and intelligent load management for public outdoor use. The prototype operated independently from the main power grid, using a 50 W monocrystalline solar panel and a 12 V sealed lead-acid battery to power a 12 V LED lamp, a 5 V DC fan, and a 5 V USB charging port, with real-time updates through the Blynk platform. Over three days of testing, the system showed stable performance, with solar current peaking between 2.1 A and 2.7 A and battery voltage staying between 12.15 V and 13.58 V. The maximum load of 9.57 W was supported without any interruption in system operation. Smart control with LDR and PIR sensors helped reduce unnecessary energy use, while QR code access made it easy for users to interact. Overall, the system met its goals and proved feasible for sustainable public shelter applications, with future plans to improve MPPT charge control, data logging, and long-term testing in the field.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

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