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Digital Twin Based Smart Building and Energy Management

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Abstract: This paper presents a smart building energy management system based on a Digital Twin. It combines real-time sensing, built-in intelligence, and cloud monitoring to improve energy awareness and operational efficiency. The Digital Twin serves as a continuously updated virtual model of the physical building, using live data from temperature, light, and energy sensors connected to an ESP32 microcontroller. A dedicated power measurement module tracks electrical energy consumption, allowing real-time checks of voltage, current, power, and energy usage for both the whole system and individual loads. The synchronized Digital Twin offers remote visualization and system insights through a cloud-based IoT platform, helping users make informed energy decisions. The system also includes safety-aware automation to enhance reliability and robustness. Experimental tests show that data synchronization is accurate and the system performs stably under different load conditions. The proposed system best describes how digital twin technology helps in effective energy management.

Keywords: Digital Twin, Smart Building, Energy Management, ESP32, IoT.

1 INTRODUCTION

In today's world, buildings rely heavily on electrical energy because of the widespread use of lighting systems, electronic devices, and automated infrastructure. Consequently, energy use in both residential and commercial buildings has increased significantly. Along with this rising energy demand, problems like inefficient use, lack of real-time monitoring, and poor operational awareness still challenge building management systems. Traditional energy monitoring methods mainly depend on static meters and manual observation, which only offer limited insight into actual energy consumption over time. With the growth of embedded systems and Internet of Things (IoT) technologies, smart building solutions have emerged to improve energy visibility and remote monitoring. While these systems support real-time data collection and cloud-based dashboards, many serve merely as monitoring tools. They do not create a strong link between the physical building environment and an ever-evolving digital model. As a result, the potential for deeper analysis, optimization, and smart decision support remains underused.

Digital Twin technology changes the game when it comes to tackling these problems. Think of a Digital Twin as a live, digital copy of a real-world system— it's always in sync with what's actually happening. For smart buildings, this means you get a virtual space that mirrors energy use and environmental conditions in real time. With everything linked together, people can see energy patterns and system performance in a way that just makes sense. In this project, I built a smart building energy management system around a Digital Twin using an ESP32 microcontroller. The system grabs real-time data—temperature, lighting, energy use—from sensors in the building and sends it straight to the cloud. The Digital Twin updates constantly, so you can check in remotely, see what's going on, and really understand how energy flows through the building. There's also built-in safety automation, which keeps everything running smoothly and reliably. This setup proves you don't need expensive hardware—a simple, affordable platform like the ESP32 can power a smart, sustainable energy management system using Digital Twin technology.

2 PROBLEM IDENTIFICATION

Effective energy management in smart buildings is still a tough problem, even with improvements in embedded systems and IoT technologies. Most current building energy solutions provide limited operational insight and do not fully utilize real-time data for better energy management. While several monitoring platforms exist, they often lack strong connections between the physical building environment and its digital model. This section outlines the main issues found in traditional and existing smart building energy management systems. Fig. 1 shows the problem statement of the proposed method.

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1. Limited real-time energy visibility:
Traditional energy monitoring systems mainly use static energy meters that provide cumulative readings over long periods. These Systems do not show Immediate changes in energy consumption, making it hard to find peak usage, load changes, etc.

2. Lack of Individual Load Monitoring:
Most existing solutions focus on total energy consumption and fail to give detailed information about individual electrical loads. Without this load level data, it is difficult to identify inefficient or high-energy-using appliances, reducing the effectiveness of energy-saving strategies.

3. Weak Connections Between Physical Systems and Digital Platforms:
While IoT-based dashboards allow remote access to energy data, they often work only as visualization tools. The lack of a continuously updated digital representation prevents these systems from functioning as true Digital Twins, limiting their ability to analyse and operate effectively.

4. Delayed Data Synchronization and Response:
Many smart energy systems refresh sensor data at set intervals instead of continuously. This delay results in outdated information and diminishes the system's capacity to respond well to quick changes in energy usage or system conditions.

5. Limited energy awareness and decision support:
Current Systems mainly focus on data collection instead of meaningful data interpretation. Consequently, users do not have a clear Understanding of Power Consumption Patterns.

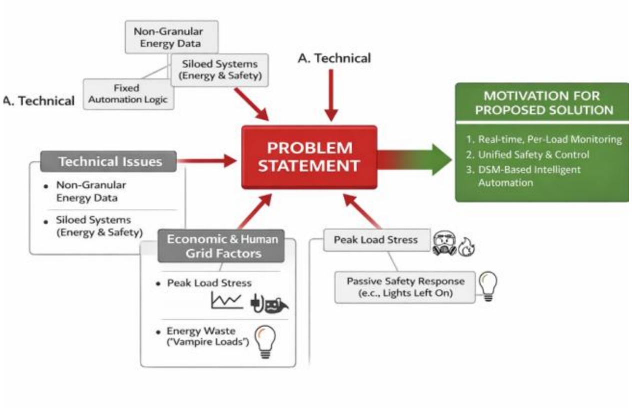


Fig. 1. Problem Statement of the Proposed Method

3 LITERATURE SURVEY

Recent advancements in digital technologies have changed traditional buildings into smart, energy-efficient, and sustainable systems. This transformation comes from integrating sensors, automation, and real-time data analysis. A smart building management system based on digital twins was created to ensure real-time synchronization between the actual building and its virtual model. This system allows constant monitoring of environmental factors like temperature, vibration, air quality, and safety conditions. It also improves operational visibility and helps with decision-making efficiency [1]. An IoT-based architectural framework was introduced to support the large-scale deployment of different sensors in buildings. This framework enables reliable, real-time data collection, communication, and automatic control. It also addresses important challenges related to growth, compatibility, and energy use in smart building environments [2]. The integration of Building Information Modelling (BIM) with sensor-driven monitoring systems aims to assess sustainability, analyse energy use throughout the building's life, and optimize performance by providing a precise digital model of building structures and systems for better decision-making [3].

Further analysis of IoT-driven smart energy management methods showed that adaptive automation and intelligent load control strategies can significantly cut down energy waste and improve energy efficiency in both homes and businesses [4]. The use of digital twin technology in built environments was expanded to support ongoing evaluation of thermal comfort, energy use, and overall building performance. This is done by syncing real-time sensor data with dynamic virtual models, thus enhancing sustainability and operational efficiency [5]. Smart building systems are also key parts of smart city infrastructure. They allow for effective monitoring and management of environmental conditions and energy usage through low-power IoT sensor networks and distributed data processing methods [6]. Cloud-based energy monitoring platforms were created to track, visualize, store, and analyze building power use in real time. This supports scalable, remote, and data-driven energy management solutions for smart buildings [7]. Investigating digital twin-based cyber-physical building systems showed how they improve predictive analysis, fault detection, and intelligent control by keeping physical assets and their digital versions in sync. This supports proactive building management [8]. Further proposals for IoT-enabled smart building frameworks focus on increasing automation, operational efficiency, and occupant comfort.

This is achieved through the integration of intelligent sensor networks with adaptive control algorithms and communication methods for real-time monitoring [9]. Multi-sensor smart building monitoring systems, which include temperature, air quality, occupancy, and safety detection, were designed to enhance indoor environment quality and operational efficiency through automated environmental control and real-time feedback mechanisms [10]. IoT-based building automation solutions were introduced to improve electrical load management and reduce overall energy use by utilizing real-time sensor data, intelligent decision-making, and automated actuation strategies [11]. Digital twin frameworks for building energy management were developed to analyse past and current energy use patterns. This allows for predictive optimization strategies, better energy planning, and proactive maintenance of building systems [12]. Recent intelligent smart building solutions that combine energy monitoring, safety detection, automation, and real-time analytics were analysed. This highlights the importance of merging IoT sensing, digital twin technology, and intelligent control methods to create sustainable, efficient, and resilient building management systems [13].

4 PROPOSED SYSTEM

Conventional smart building monitoring systems mainly focus on basic sensing and manual control of electrical loads. Most current systems only offer simple ON/OFF automation without detailed energy monitoring or real-time visualization of each load's consumption. In many instances, safety features like fire alerts are limited to local notifications and do not provide remote alerts or automatic responses. Also, traditional systems do not present per-load power analysis, billing estimates, or visual representations of energy usage. This makes it hard for users to monitor and improve their energy consumption effectively. These limitations lower the overall efficiency, safety, and intelligence of standard building management solutions.

4.1. Proposed System Overview

To address the issues of traditional smart building systems, we propose an IoT-based smart building management system. This system includes safety automation, load prioritization based on demand response, and real-time energy monitoring. The main goal is to automate building operations and reduce unnecessary electricity use through intelligent sensing, automatic control, and user awareness. The system continuously monitors the environment using a temperature sensor, LDR, and flame sensor. It controls electrical appliances and AC loads through a relay module. Automatic lighting control relies on the LDR sensor, which detects ambient light levels. It turns on the light strip only when natural light is lacking, eliminating the need for manual operation and preventing energy waste from lights that stay ON during the day or in well-lit areas. Since lighting significantly affects overall energy use in buildings, this automation leads to noticeable electricity savings. The temperature sensor constantly tracks indoor temperatures and sends real-time updates to the IoT platform. While the system doesn’t directly control cooling devices, it displays real-time temperature data.

This allows users to make better choices about when to use appliances, which can indirectly lower energy use and improve comfort. We implement safety automation using a flame sensor, which is vital for preventing damage and energy loss in dangerous situations. When a flame or fire is detected, the system activates an exhaust fan to remove smoke and sounds a buzzer for audible alerts inside the building. Additionally, it sends a notification to the user through the Blynk IoT app. This automatic response reduces the time that electrical loads remain active during unsafe conditions, cutting down on safety risks and unnecessary power usage. To boost energy efficiency, the system features a manual demand response strategy using a simple control switch. When the demand response switch is turned ON, the system shifts into energy-saving mode, keeping only high-priority loads—like essential lighting and safety devices—active. All non-essential loads are switched OFF automatically via relay control. This strategy is especially effective during peak times, emergencies, or user-defined energy-saving periods, significantly lowering overall power use while maintaining essential services.

A standout feature of the proposed system is load-specific energy monitoring with a PZEM power measurement module. The PZEM module tracks voltage, current, real-time power, cumulative energy use, and estimated billing for each load. This detailed monitoring helps users identify which appliances use the most electricity and assess their usage habits. All collected data is sent to the Blynk IoT platform, where users can see individual load consumption, billing details, and graphical views of energy use over time. This visualization raises user awareness and supports responsible electricity usage by clearly showing the impact of each load on total energy consumption. By integrating automatic lighting control, safety automation, demand response with load prioritization, and real-time energy visualization, the proposed system offers an effective and user-friendly way to manage energy in smart buildings. The combination of IoT technology and intelligent control methods ensures less electricity waste, improved safety, and better operational efficiency, making the system ideal for sustainable and energy-efficient smart building applications.

4.2. Block Diagram of Proposed System

The block diagram of the proposed smart building management system shows how sensing units, control and processing modules, energy monitoring components, communication interfaces, and actuator units interact. The system aims to provide automatic control, safety response, demand response-based load management, and real-time energy monitoring. Environmental and safety parameters are detected using the LDR, temperature sensor, and flame sensor. The LDR constantly checks the ambient light intensity and sends input to the controller for automatic lighting control. This ensures that lighting loads operate only when needed. The temperature sensor measures indoor temperature and sends real-time data for monitoring and visualization. This lets users see environmental conditions through the IoT platform. The flame sensor detects fire-related incidents and quickly alerts the controller to start safety actions like activating the exhaust fan and buzzer. The ESP32 microcontroller processes all sensor data. It serves as the central decision-making and control unit of the system.

The ESP32 is chosen for its strong processing ability, low power use, and built-in Wi-Fi functionality, making it ideal for IoT-based smart building applications. Based on set threshold conditions and control logic, the ESP32 sends control signals to operate the relay module, buzzer, and exhaust fan. The ESP32 also manages demand response operations, where a manual demand response switch allows for priority-based load control. This means it can enable only essential loads while disconnecting non-critical ones during peak demand or emergencies. For energy monitoring, the ESP32 connects with a PZEM energy measurement module. This module collects real-time electrical parameters like voltage, current, power consumption, energy usage, and estimated billing values for individual AC loads. The ESP32 shares this data with the Blynk IoT platform using its built-in Wi-Fi. This allows for real-time visualization, graphical displays of energy consumption, and alert notifications. Thus, the ESP32 acts as a single platform for sensing, processing, communication, automation, and smart energy management in the proposed smart building system.

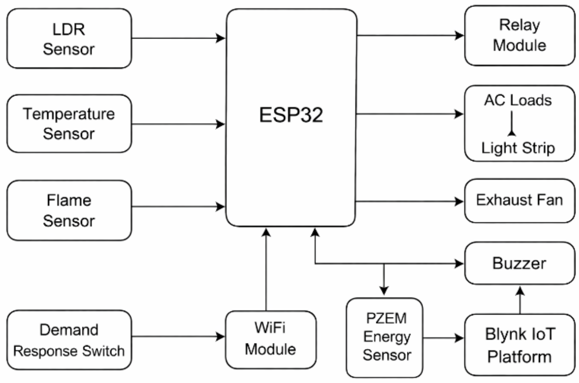


Fig. 2. Block Diagram of the Proposed System

4.3. Hardware Architecture

The hardware setup of the proposed smart building management system includes sensing units, a processing and communication unit, power monitoring modules, control interfaces, and actuator components. Each hardware part is chosen to ensure reliable operation, energy efficiency, and easy integration with the IoT platform.

1. **ESP32 Microcontroller:** The ESP32 microcontroller acts as the central control unit of the proposed system. It handles sensor data, runs control logic, manages demand response tasks, and communicates with the IoT platform. The ESP32 is selected for its strong processing ability, low power usage, and built-in Wi-Fi support, which removes the need for an outside communication module. Its integrated wireless connection allows real-time data transfer to the Blynk IoT platform, making it ideal for smart building uses.
2. **LDR Sensor:** The Light Dependent Resistor (LDR) measures the amount of light in the building. The LDR sends analog input to the ESP32 to assess lighting conditions. Based on set threshold values, the controller automatically turns the light strip on or off. This automatic control lowers unnecessary power use and improves overall energy efficiency.
3. **Temperature Sensor:** The temperature sensor continuously checks indoor temperature levels. The measured temperature values go to the ESP32 and are updated in real time on the IoT platform. Though the temperature sensor doesn't directly control any device, it gives useful environmental data to the user. This helps users make informed choices about comfort and energy usage.
4. **Flame Sensor:** The flame sensor is an important safety feature of the system. It detects fire or flame events. When it finds a flame, the sensor immediately signals the ESP32. The controller then triggers safety actions, such as turning on the exhaust fan and buzzer, while also sending alert notifications to the user through the IoT platform. This process ensures a quick response and reduces potential damage.

5. **Relay Module:** A relay module controls several AC electrical loads in the building. The relay connects the low-voltage ESP32 with high-voltage AC appliances. Based on signals from the ESP32, the relay turns connected loads, like the light strip and exhaust fan, on or off. The relay module also helps manage priority-based load control during demand response operations.
6. **PZEM Energy Measurement Module:** The PZEM energy measurement module monitors electrical details of individual AC loads. It tracks voltage, current, power, energy use, and estimated billing values in real time. The ESP32 gathers this information from the PZEM module and sends it to the IoT platform. Monitoring energy use per load helps users spot usage patterns and identify energy-hungry appliances.
7. **Demand Response Switch:** A manual demand response switch is included for priority-based load management. When turned on, the system goes into an energy-saving mode where only high-priority loads stay active, while non-essential loads disconnect automatically through relay control. This straightforward mechanism helps cut electricity use during peak times or emergencies.
8. **Actuator Units:** The actuator units in the system include a light strip, an exhaust fan, and a buzzer. The light strip is automatically controlled based on LDR input to ensure effective lighting. The exhaust fan turns on during flame detection to remove smoke and enhance safety. The buzzer gives an audible warning during dangerous situations. These actuators allow for automated responses and improve both safety and energy efficiency.

5 SOFTWARE ARCHITECTURE AND CONTROL LOGIC

The software architecture of the proposed smart building management system outlines how data is gathered, decisions are made, communication happens, and control operations are carried out by the ESP32 microcontroller. The software aims for reliable sensing, automated control, safety response, load management based on demand response, and real-time energy monitoring through the IoT platform.

1. **System Firmware Design:** The ESP32 is programmed with firmware developed in the Arduino IDE. This firmware initializes all sensors, relay modules, the PZEM energy measurement module, and the Wi-Fi communication interface when the system starts. Sensor values from the LDR, temperature sensor, and flame sensor are read and processed continuously in real time. The system uses threshold-based logic to decide on control actions, such as switching loads, triggering alerts, and activating safety mechanisms.
2. **Control Logic and Automation:** The control logic of the system relies on set conditions and priority rules. When the LDR detects low ambient light, the ESP32 turns on the light strip through the relay module. The temperature sensor always provides updated environmental data, which is shown on the IoT platform for monitoring. If a flame is detected, the ESP32 quickly runs safety routines by activating the exhaust fan and buzzer. At the same time, the system sends an alert notification to the user through the IoT platform. This automated response allows for quick action during dangerous situations and reduces the need for manual intervention.
3. **Demand Response and Priority-Based Load Control:** A manual demand response switch is included in the software logic for priority-based load management. When this mode is turned on, the ESP32 disables all non-critical electrical loads through the relay module and keeps only high priority loads active. This approach lowers electricity use during peak demand times or emergencies while ensuring essential services remain available. When the switch is turned off, the system goes back to normal operation.
4. **Energy Monitoring and Data Processing:** The ESP32 connects with the PZEM energy measurement module to gather real-time electrical data such as voltage, current, power, and total energy consumption for individual AC loads. The system processes these values and formats them for sending to the IoT platform. It also calculates estimated billing information based on energy usage, helping users understand the costs of each connected load.
5. **IoT Communication and Visualization:** The ESP32's built-in Wi-Fi capability allows it to communicate with the Blynk IoT platform. It sends sensor data, energy measurements, and system status information to the cloud in real time. The Blynk application offers a simple interface for visualizing sensor values, energy consumption for each load, billing details, and graphical trends over time. The system also sends alert notifications to the user in case of unusual conditions like flame detection or demand response activation.

6 THEORETICAL FRAMEWORK AND PRIORITY-BASED LOAD MANAGEMENT

The proposed smart building management system uses a Priority-Based Load Control (PBLC) strategy to manage electrical loads effectively during peak demand and emergencies. The main goal is to keep high-priority loads running while reducing overall electricity use by temporarily shutting off non-critical loads. Unlike traditional manual load control methods, this system employs automated decision-making with the ESP32 microcontroller, relay modules, and a demand response switch. Each electrical load connected to the system gets a set priority level based on its importance. Under normal conditions, all loads function as needed. When the demand response switch is turned on, the system goes into energy-saving mode. In this mode, only high-priority loads stay on, and low-priority loads are automatically turned off. This process effectively lowers peak power demand and avoids unnecessary energy consumption.

The electrical loads connected to the system are divided into three priority categories:

- **Critical Loads:** These loads must stay ON in all conditions for safety or essential operation.
- **Essential Loads**: These loads are necessary for basic comfort and functionality.
- **Non-Critical Loads**: These loads can be temporarily disconnected without impacting safety.

This classification allows for smart and flexible energy management while ensuring user comfort and safety.

Table 1. Appliance Priority and Controller Action Matrix

Appliance Name	Approx. Load (Watts)	Priority Category	Controller Action
LED Lamps / Tube Lights	20–40 W	Critical	Permitted (Always ON)
Refrigerator	200–400 W	Critical	Permitted (Maintains Cooling)
Ceiling Fan	60–80 W	Essential	Permitted (Base Comfort)
Smart TV / Laptop	100–150 W	Essential	Permitted
Air Conditioner (AC)	1500 W+	Non - Critical	Shut during Demand Response
Water Geyser	2000 W+	Non - Critical	Shut during Demand Response

7 RESULTS AND DISCUSSION

The proposed IoT-based smart building management system was successfully implemented and experimentally tested to evaluate its automation performance, safety response capability, demand response operation, and real-time energy monitoring functionality. The system demonstrated reliable performance under different environmental and load conditions, confirming the effectiveness of integrating sensing modules, relay-based control, and IoT-based visualization through the ESP32 microcontroller platform. The safety automation functionality of the system was tested to verify its response under normal operating conditions. During testing, the system maintained safe operational status while continuously monitoring environmental conditions and electrical load behaviour. The safe operating condition of the system during normal operation is illustrated in Fig. 3, which confirms the stability and reliability of the implemented smart building management platform.

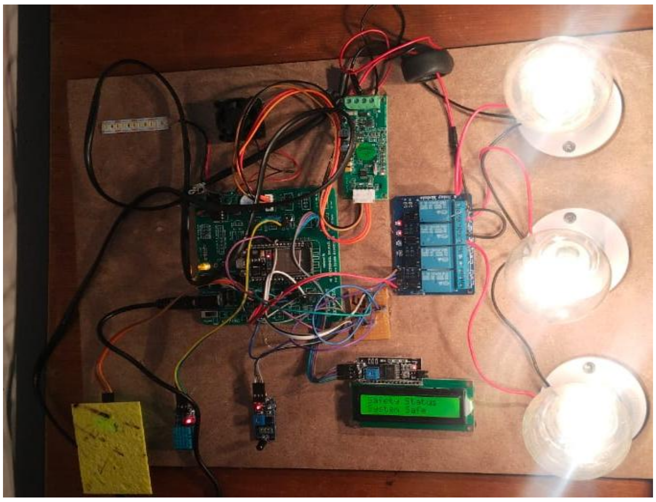


Fig. 3. System Safe

The flame detection mechanism was evaluated by introducing controlled flame conditions near the flame sensor module. When flame presence was detected, the ESP32 microcontroller immediately activated the exhaust fan and buzzer while simultaneously sending alert notifications through the Blynk IoT platform. This automatic response demonstrates the effectiveness of the safety automation subsystem in preventing hazardous situations and reducing potential risks in building environments. The fire detection response of the system is shown in Fig. 4. The LDR-based automatic lighting control mechanism was tested under varying ambient light conditions to verify its energy-saving capability. When the ambient light level decreased below the predefined threshold value, the ESP32 controller automatically activated the lighting load through the relay module. Similarly, when sufficient natural light was available, the lighting load was switched OFF automatically to prevent unnecessary power consumption. The status of automatic lighting control based on LDR sensing is shown in Fig. 5, confirming the effectiveness of the intelligent lighting automation feature.

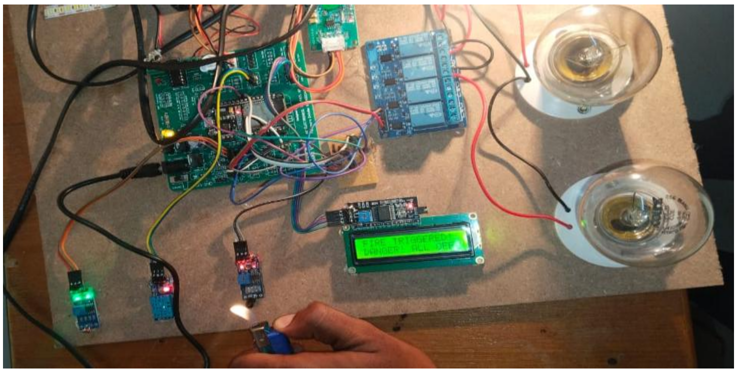


Fig. 4. Fire Detection

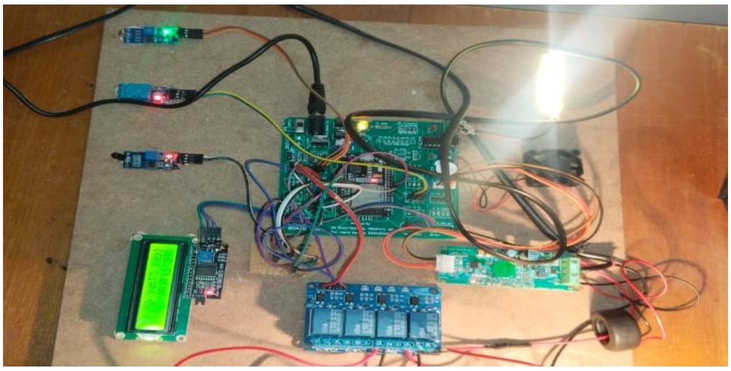


Fig. 5. LDR Status

The Demand Side Management (DSM) functionality of the proposed system was evaluated using the manual demand response switch integrated into the controller unit. When DSM mode was activated, the system successfully disconnected non-critical loads while maintaining operation of essential loads such as safety devices and lighting units. This priority-based load control strategy effectively reduced peak power demand and improved overall energy utilization efficiency. The operational status of DSM-based load control is illustrated in Fig. 6, validating the effectiveness of the implemented priority-based load management approach.

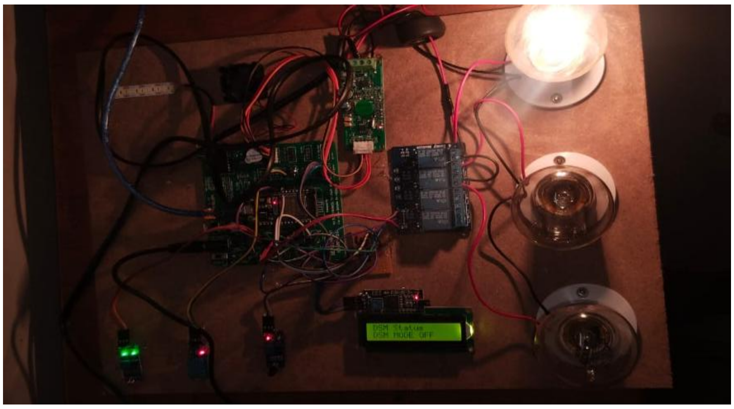
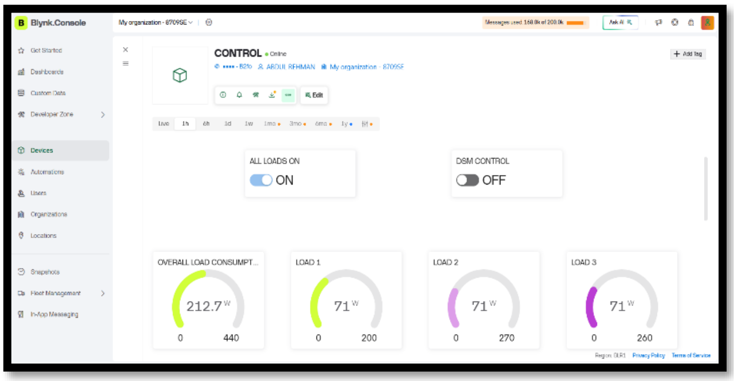


Fig. 6. DSM Status

The real-time visualization capability of the proposed smart building management system was tested using the Blynk IoT platform interface. Sensor readings, system status information, and electrical load parameters were successfully transmitted from the ESP32 controller to the cloud platform through wireless communication. The Blynk dashboard enabled users to monitor environmental conditions and load operation remotely through a mobile interface. The real-time monitoring interface of the system is presented in Fig. 7, demonstrating effective IoT-based remote visualization capability.

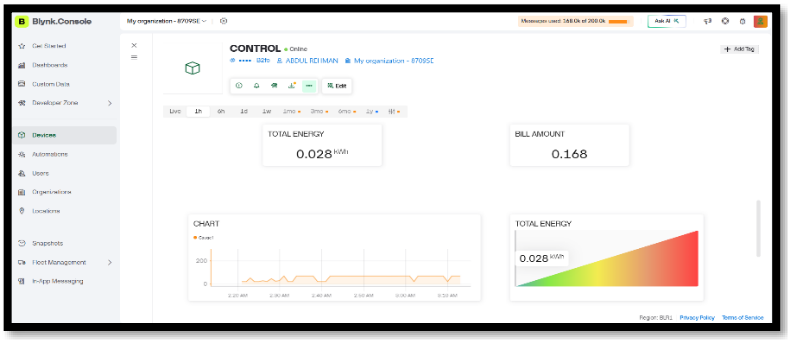


ALL LOADS ON
ON

DSM CONTROL
OFF

Fig. 7. Blynk Visualization

The energy monitoring functionality of the system was validated using the PZEM energy measurement module to track electrical parameters such as voltage, current, power consumption, cumulative energy usage, and estimated billing values. These parameters were continuously transmitted to the Blynk platform and displayed through graphical charts for easy interpretation. The power consumption monitoring interface is shown in Fig. 8, confirming accurate measurement and visualization of electrical energy usage.



TOTAL ENERGY
0.028 kWh

BILL AMOUNT
0.168

Fig. 8. Blynk Power Consumption Charts

Further analysis of system performance was carried out using graphical visualization of electrical parameter variations over time through the Blynk platform. These graphical trends provided clear insights into load behavior during normal operation and demand response conditions. The visualization of energy usage trends supports improved user awareness and assists in making informed energy-saving decisions. The graphical representation of system performance is illustrated in Fig. 9, confirming the effectiveness of the proposed IoT-enabled monitoring architecture.

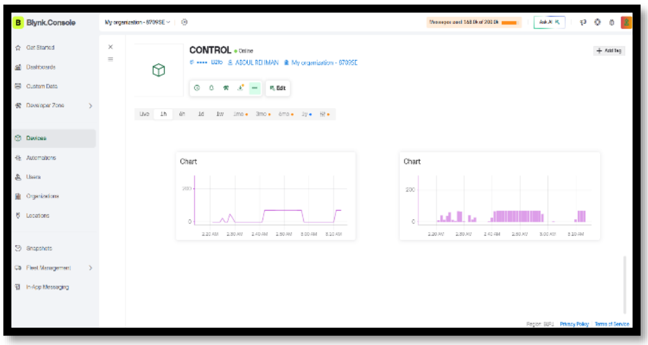


Fig. 9. Blynk Graphs

8 CONCLUSION

This paper describes an IoT-based smart building management system that includes safety automation, load prioritization based on demand response, and real-time energy monitoring. The system used an ESP32 microcontroller, environmental sensors, relay-based load control, and a PZEM energy measurement module to allow for intelligent monitoring and control of building loads.

Automatic lighting control was implemented with LDR, a flame-based safety response featuring exhaust ventilation and alerts, and priority-based demand response operation. The real-time visualization of individual load consumption, billing estimates, and graphical analysis through the Blynk IoT platform improved user awareness and energy-efficient decision-making. Experimental results showed that the system effectively reduces peak power demand and electricity costs, matching closely with the theoretical demand-side management analysis. This system offers a reliable, scalable, and cost-effective solution for energy-efficient and safe smart building management.

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This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

ETHICS STATEMENT

This study did not involve human or animal subjects and, therefore, did not require ethical approval.

STATEMENT OF CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interest related to this study.

LICENSING

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