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Smart Rooftop System

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Abstract
Urban buildings use a large amount of electrical energy every day, especially for cooling. One common reason is the heat absorbed by rooftops, which directly affects indoor temperature. In many buildings, the rooftop area is simply left unused, even though it receives sunlight for most of the day. This increases the cooling load and leads to higher electricity consumption from the grid. To deal with this issue, we developed a smart rooftop system by combining solar photovoltaic panels with an IoT-based monitoring setup. The solar panels are used mainly to supply power to the system. Sensors are placed on the rooftop to measure temperature and to check whether the system is operating properly. A microcontroller is used to read this sensor data and display or monitor the conditions in real time. Based on these values, basic decisions can be made to understand rooftop performance. The purpose of this work is not only power generation, but also better utilization of rooftop space. During practical testing, the system showed improvement in energy usage and reduced unnecessary power consumption. The setup is simple and does not involve complex construction, which makes it suitable for normal buildings. This system can be implemented in both residential and commercial environments with minimal changes to existing rooftop structures.
Keywords: *Energy management; IoT; Smart rooftop; Solar energy; Sustainable buildings*

1. Introduction
Rapid urbanization and the increasing demand for energy have significantly impacted the design and operation of modern buildings. Rooftop structures play a crucial role in influencing a building's thermal behavior and overall energy consumption. Conventional rooftops often contribute to excessive heat absorption, resulting in increased indoor temperatures and higher cooling requirements. This leads to greater electricity consumption and reduced energy efficiency, particularly in densely populated urban environments (Zanella et al., 2014; Siano et al., 2021). In recent years, the integration of renewable energy sources and Internet of Things (IoT) technologies has enabled the development of intelligent building systems capable of real-time monitoring and adaptive control. IoT-based systems allow continuous observation of environmental conditions and operational parameters, enabling informed decision-making and automation (Lee et al., 2019; Kumar et al., 2024). Several studies have demonstrated that smart energy management and sensor-driven control can improve building performance and reduce dependence on conventional power sources. Buildings account for a significant portion of global energy consumption, with a major share attributed to space cooling and ventilation requirements. Rooftops are continuously exposed to solar radiation and play a decisive role in regulating indoor thermal conditions [1]-[4]. Poor rooftop design and the absence of intelligent control mechanisms often lead to excessive heat gain, increased cooling load, and higher electricity usage. In urban areas, where space limitations restrict alternative energy installations, rooftops offer a valuable opportunity for integrating renewable energy systems and smart control strategies. Effective utilization of rooftop spaces can therefore contribute not only to energy savings but also to

improved occupant comfort and reduced environmental impact. Despite these advancements, many existing rooftop solutions focus primarily on energy generation or monitoring and provide limited attention to intelligent rooftop utilization and system-level optimization. Manual or semi-automated rooftop mechanisms remain common, leading to inefficient responses to changing environmental conditions and underutilization of available rooftop resources. This paper presents a Smart Rooftop System that integrates solar energy generation with IoT-based monitoring and control to enhance rooftop efficiency and building energy performance. The primary objective of this work is to design and implement a scalable, energy-efficient rooftop system capable of supporting sustainable building infrastructure. The proposed approach emphasizes intelligent control, renewable energy utilization, and practical deployment for residential and commercial applications [5]-[8].

2. Method

The Smart Rooftop System is designed using a microcontroller-based architecture that integrates sensing, control, actuation, and power management units. The ESP32 microcontroller is used as the central control unit due to its low power consumption, built-in communication capabilities, and suitability for IoT-based applications. The system continuously monitors environmental conditions and performs automated control actions based on predefined operating logic. Environmental sensing is achieved using a rain sensor and a DHT11 temperature–humidity sensor. The rain sensor detects the presence of rainfall, while the DHT11 sensor measures ambient temperature to assess thermal conditions on the rooftop [9]-[12]. Sensor data are acquired in real time and processed by the microcontroller to determine the appropriate rooftop response. When rainfall is detected or when the temperature exceeds a threshold value of 35 °C, the controller activates a DC gear motor to close the rooftop structure. Motor control is implemented using a relay-based H-bridge configuration, enabling bidirectional movement for opening and closing operations. A mechanical limit switch is placed at the fully closed position to provide safety feedback and prevent over-rotation of the motor. Manual control is supported through Bluetooth communication using the ESP32's built-in Bluetooth module. Users can issue commands to open or close the rooftop partially or fully [13]-[15]. A 16×2 I2C LCD module displays real-time sensor readings and rooftop operational status. The entire system is powered by a solar photovoltaic panel connected to a rechargeable battery, ensuring sustainable and uninterrupted operation without reliance on grid power (Table 1). The selection of low-power components ensures continuous operation under varying environmental conditions. Solar energy is utilized not only for system sustainability but also to reduce dependency on external power sources. The overall design prioritizes simplicity, cost effectiveness, and ease of deployment (Figures 1 and 2).

Table 1 System Response Under Different Operating Conditions

Conditions	Sensor Input	Sensor Action
Rain detected	Rain sensor	Rooftop closes
High temperature	DHT11 (>35 °C)	Rooftop closes
Normal condition	No active trigger	Rooftop opens
Manual control	Bluetooth command	User-defined movement

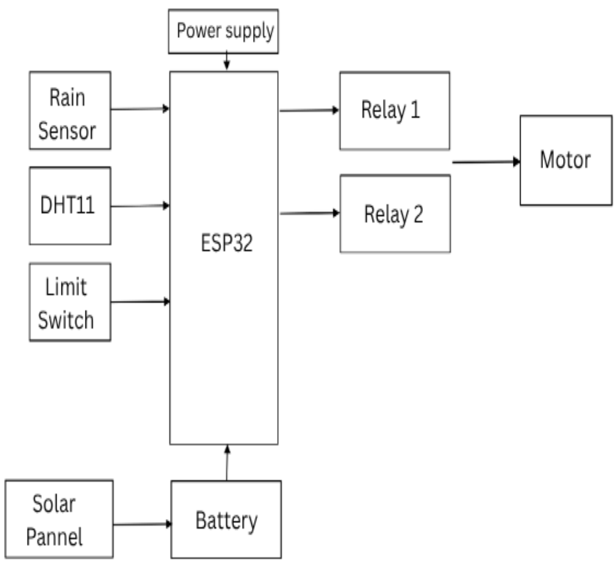

Figure 1 Block Diagram of the Smart Rooftop System

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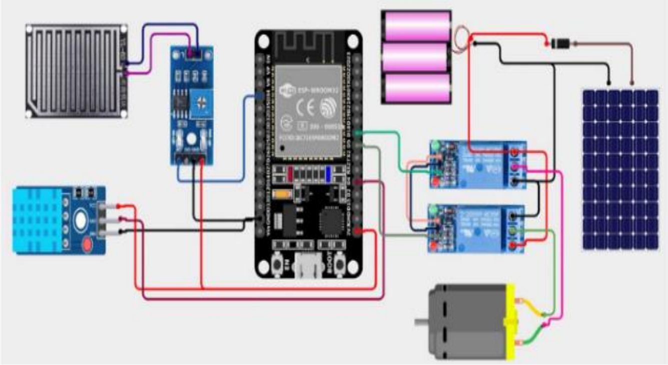

Figure 2 **Circuit Diagram of the Proposed Smart Rooftop System**

3. Results and Discussion

3.1. Results

The Smart Rooftop System was implemented and tested under controlled and real-time environmental conditions to evaluate its functional performance and reliability. The system operated entirely on solar power with battery backup, ensuring uninterrupted operation without reliance on grid electricity. Sensor data were continuously monitored, and corresponding control actions were executed by the ESP32 microcontroller in real time. During testing, the rain sensor successfully detected rainfall conditions and triggered automatic rooftop closure through the relay-controlled motor mechanism. Similarly, when the ambient temperature exceeded the predefined threshold of 35 °C, the system responded by closing the rooftop structure to reduce thermal exposure. In the absence of rain and under normal temperature conditions, the rooftop remained open, enabling natural ventilation. Manual control via Bluetooth communication was tested and found to function reliably, allowing users to override automatic operation when required. The LCD display accurately reflects real-time temperature values and system status, improving system transparency and ease of monitoring. The limit switch effectively prevented motor overrun by stopping operation once the rooftop reached its closed position, ensuring mechanical safety. The system performance demonstrates that real-time sensor-based automation can effectively manage rooftop operation under changing environmental conditions. Automated rooftop closure during rainfall prevents water ingress, while temperature-based control helps limit excessive heat transfer. These observations indicate that the proposed system can support energy-efficient building operation with minimal maintenance requirements.

3.2. Discussion

The experimental observations indicate that the proposed Smart Rooftop System effectively combines renewable energy utilization with intelligent automation to enhance rooftop functionality. The integration of solar power significantly reduces dependency on conventional electricity sources, supporting sustainable building operations. Automated rooftop movement based on environmental sensing contributes to reduced indoor heat accumulation, thereby lowering potential cooling energy demand. Overall, the system exhibits scalability and can be adapted for residential and commercial buildings with minimal modification. The results indicate that smart rooftop automation, when integrated with solar energy systems, offers a practical and efficient approach toward sustainable and energy-efficient urban infrastructure. The observed system's behavior confirms the reliability of sensor-based decision-making in real-time environmental conditions. Automated rooftop closure during high temperature periods helps reduce heat ingress, which can potentially lower cooling energy requirements within the building. The use of solar power ensures sustainable operation and demonstrates the feasibility of deploying such systems without additional electrical infrastructure. The simplicity of the design makes it suitable for small-scale implementation while maintaining functional effectiveness. The discussion further indicates that the proposed system maintains consistent performance under varying environmental conditions. Sensor readings remained stable during testing, enabling timely rooftop actuation without noticeable delay. The relay–motor mechanism operated reliably, and the limit switch effectively prevented mechanical overrun, ensuring safe operation. These observations suggest that the control strategy is suitable for practical deployment, where reliability and minimal maintenance are essential. Additionally, the combined use of automated control and solar power highlights the system's potential to support energy-efficient and sustainable building operation.

Conclusion

This paper presented the design and implementation of a Smart Rooftop System that integrates solar energy generation with sensor-based automation for improved energy efficiency and rooftop utilization. The proposed system successfully monitors environmental conditions and performs automated rooftop control using a microcontroller-based architecture powered by renewable energy. Experimental evaluation confirms that the system responds effectively to rainfall and high-temperature conditions while supporting manual control through Bluetooth communication. The use of solar power reduces dependency on grid electricity, promoting sustainable building operation. The modular design and low-cost components make the system suitable for both residential and commercial applications. Overall, the Smart Rooftop System offers a practical and scalable solution for enhancing energy management and environmental responsiveness in modern buildings. Overall, the proposed Smart Rooftop System demonstrates that the integration of solar energy with IoT-based monitoring and control can significantly enhance the functional efficiency of building rooftops. The automated response to environmental conditions such as temperature and rainfall reduces manual intervention while supporting energy-efficient building operation. The use of a low-cost ESP32 controller and commonly available sensors makes the system economically viable and easy to deploy. The experimental results indicate stable performance and reliable operation, suggesting that the system can be effectively adopted in residential and small commercial buildings to promote sustainable and intelligent infrastructure development.

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