International Journal of Multidisciplinary Informative Research and Review
2025; 2(3): 38 - 45
Published online May 30, 2025 (https://agribusinessedu.com/ijmirr-journal/)
DOI: 10.5281/zenodo.18639817
ISSN: 2709-6289 (Online)

A Solar-Powered IoT-Enabled Smart Bus Stop for Sustainable Public Transportation and Crowd Monitoring

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To cite this article:
Md. Niaz Mostakim, Md. Khalid Hossain Jewel, Md. Tajrul Islam, Md. Rabiul Islam, Md. Younus Miah. A Solar-Powered IoT-Enabled Smart Bus Stop for Sustainable Public Transportation and Crowd Monitoring. *International Journal of Multidisciplinary Informative Research and Review* .Vol. 2, No. 3, 2025, pp. 38 - 45.

Abstract: This paper presents an Internet of Things (IoT) based smart bus stop system integrated with renewable energy harvesting and automated crowd monitoring. The proposed system utilizes a solar panel with MPPT charge controller and battery storage to ensure sustainable and grid-independent operation. Infrared sensors are deployed to detect passenger movement, count boarding and alighting individuals, and monitor crowd density within the shelter. Additionally, the system detects bus arrival and departure events and transmits real-time data including passenger count, solar voltage, battery voltage, and bus status to an IoT monitoring platform. A timing control mechanism activates an alert when buses remain stationary for excessive durations, helping to maintain operational discipline. The system demonstrates a cost-effective and eco-friendly solution for modern smart city transportation infrastructure. Experimental implementation confirms reliable performance in energy management, crowd monitoring, and real-time data transmission. The proposed design contributes toward sustainable urban transport management by improving passenger convenience, operational efficiency, and energy utilization.

Keywords: IoT, Smart Bus Stop, Renewable Energy, Solar Power, Crowd Monitoring, Smart Transportation.

1. Introduction

Rapid urbanization demands efficient and sustainable public transportation infrastructure. Recent initiatives have introduced smart bus shelters; however, many lack remote monitoring, energy optimization, and automated management features. Manual maintenance and delayed fault detection reduce system efficiency and increase operational costs. With increasing population density in metropolitan areas, traditional transport infrastructure struggles to provide real-time passenger information, energy efficiency, and system reliability.

The Internet of Things (IoT) has emerged as a transformative technology for smart city development, enabling interconnected devices to collect, process, and transmit real-time data for improved decision-making and automation. IoT-based monitoring systems have already been applied in smart transportation, vehicle tracking, and environmental monitoring applications, demonstrating improvements in operational control and service reliability [1], [2]. For instance, IoT-enabled vehicle tracking systems using GPS, RFID, and wireless communication technologies have significantly enhanced route monitoring and passenger information systems [3]. Similarly, wireless sensor networks have been used to monitor environmental conditions, air quality, and traffic congestion in urban areas, contributing to intelligent transportation planning [4], [5].

Despite these advancements, limited research has focused on improving the infrastructure of bus stops themselves. Most existing systems concentrate on tracking vehicles rather than optimizing passenger waiting environments or energy usage at bus shelters. Smart bus stop solutions deployed in some cities provide comfort features such as air-conditioning and digital displays but often lack integrated monitoring, renewable energy support, and crowd analysis capabilities [6].

This research proposes an IoT-based smart bus stop that integrates sensors, automation, and renewable energy to enhance operational efficiency. The system collects environmental and operational data using sensors and transmits it for real-time monitoring. By tracking passenger density and bus movement, the system enables intelligent energy management and improved service delivery. The approach aligns with smart city development goals by improving public transport sustainability, reducing energy consumption, and enabling automated infrastructure management. Such systems contribute to energy conservation, improved passenger experience, and optimized transport resource utilization, which are key priorities in modern smart urban ecosystems [7].

2. Literature Review

The Internet of Things (IoT) has become a key enabler of smart city infrastructure by facilitating communication among sensors, embedded devices, and cloud platforms to support automation and data-driven decision making. In transportation systems, IoT technologies have been widely used for vehicle tracking, passenger information systems, and route optimization. Several studies have proposed IoT-based bus monitoring systems utilizing RFID, GPS, and wireless communication technologies to track vehicles and estimate arrival times, thereby improving service reliability and passenger safety [8], [9]. Wireless sensor networks have also been applied for environmental monitoring within smart transportation frameworks. Systems integrating gas sensors, mobile communication modules, and cloud platforms have been deployed to measure air pollution levels in urban areas, contributing to intelligent city planning and public health monitoring [10]. Similarly, Bluetooth-based monitoring and tracking systems have been used to collect vehicle movement data along urban roads, enabling authorities to analyze traffic patterns and optimize transport flow [11]. ZigBee-enabled sensing frameworks have further demonstrated the potential of distributed wireless networks for monitoring environmental parameters such as temperature, humidity, and dust concentration in urban environments [12].

Beyond vehicle tracking, IoT technologies have also supported intelligent infrastructure applications such as RFID-based parking management systems and automated traffic monitoring platforms, which help reduce congestion and improve operational efficiency [13]. Vision-based approaches using cameras and image processing algorithms have additionally been explored to monitor traffic density, detect incidents, and enhance road safety [14]. Despite these advancements, most existing research focuses on monitoring vehicles or environmental conditions rather than improving passenger waiting infrastructure such as bus shelters. Although modern smart bus stops in some cities offer features such as digital displays and climate control, many lack integrated renewable energy systems, automated crowd monitoring, and real-time operational analytics. The absence of these features limits the sustainability and scalability of smart transport infrastructure [15]. To address this gap, recent research has emphasized integrating renewable energy with IoT-enabled infrastructure. Solar-powered IoT systems can operate autonomously while reducing dependency on grid electricity, making them suitable for sustainable urban transport applications [16]. Therefore, this study proposes an IoT-based smart bus stop that combines renewable energy harvesting, passenger monitoring, and real-time data transmission. The proposed approach enhances operational efficiency, passenger experience, and energy sustainability, supporting the long-term vision of smart city transportation systems.

3. Methodology

The proposed system is designed as a solar-powered IoT-enabled monitoring platform that integrates renewable energy harvesting, sensing, data processing, and wireless communication. The architecture is divided into four primary modules: the energy harvesting unit, sensing unit, control and processing unit, and communication interface.

The energy harvesting unit consists of a photovoltaic solar panel that converts solar radiation into electrical energy. The generated power is regulated using a Maximum Power Point Tracking (MPPT) charge controller to ensure efficient charging under varying sunlight conditions. The stored energy in a rechargeable battery provides uninterrupted power supply to the system, enabling autonomous operation even during low solar availability. A DC–DC buck converter is used to regulate the output voltage and ensure stable power delivery to the microcontroller and peripheral devices. The sensing unit incorporates multiple infrared (IR) sensors strategically placed within the bus stop environment. These sensors detect passenger movement, count boarding and alighting individuals, and identify the presence of buses. By continuously monitoring these parameters, the system can estimate crowd density and bus activity in real time. The sensing data is transmitted to the processing unit for analysis and decision making. The control and processing unit is built around a NodeMCU microcontroller, which acts as the central computing module of the system. It processes sensor signals, manages energy consumption logic, and controls output devices such as the buzzer. A timing mechanism is implemented within the controller to evaluate bus dwell time. If a bus remains at the stop longer than a predefined threshold, the system automatically triggers an audible alert to improve operational discipline and minimize delays. The communication interface utilizes the built-in Wi-Fi capability of the NodeMCU module to transmit data to an IoT cloud platform. Real-time parameters such as passenger count, bus arrival status, solar voltage, and battery level are uploaded to the platform for monitoring and analysis. This wireless connectivity enables remote supervision of the bus stop infrastructure through a web or mobile dashboard, facilitating data-driven management decisions.

4. System Design and Implementation

4.1. System Architecture and Design

The proposed smart bus stop system is designed using a modular architecture that integrates renewable energy harvesting, sensor-based monitoring, embedded control, and wireless communication. The architecture ensures autonomous operation, low power consumption, and real-time data availability for monitoring and decision-making. At the core of the system is the energy harvesting subsystem, which consists of a photovoltaic solar panel used to convert solar radiation into electrical energy. The generated energy is routed through a Maximum Power Point Tracking (MPPT) charge controller to maximize power extraction under varying sunlight conditions. This controller regulates voltage and current levels while protecting the battery from overcharging and deep discharge. The stored energy in the rechargeable battery serves as the primary power source, enabling uninterrupted system functionality even during nighttime or cloudy conditions. A DC–DC buck converter is incorporated to provide stable voltage levels required by the microcontroller, sensors, and communication modules.

The sensing subsystem is responsible for monitoring environmental and operational parameters at the bus stop. Infrared (IR) sensors are deployed to detect passenger movement, count individuals entering or leaving the bus, and identify bus arrival or departure events. These sensors operate based on object detection and interruption of infrared beams, allowing accurate monitoring of passenger flow and bus activity. The collected sensor data is forwarded to the processing unit for analysis and decision-making. The processing subsystem is implemented using a NodeMCU microcontroller equipped with built-in Wi-Fi capability. This controller performs multiple functions, including sensor data acquisition, processing, timing evaluation, and system control. A dwell-time monitoring algorithm is implemented to determine how long a bus remains at the stop. If the bus exceeds the allowed waiting time, the controller triggers a buzzer alert to maintain operational discipline and reduce delays. The controller also manages energy-efficient operation by ensuring that system components consume minimal power while maintaining performance. The communication subsystem enables remote monitoring and data visualization. The NodeMCU operates in Access Point (AP) or station mode to establish a wireless connection with a cloud-based IoT platform or mobile device. Real-time data such as passenger count, bus status, solar voltage, and battery level are transmitted via Wi-Fi to the monitoring interface. Through an Android-based dashboard or web interface, users can visualize system performance and receive alerts instantly. This connectivity allows authorities to remotely supervise infrastructure conditions and respond quickly to operational issues.

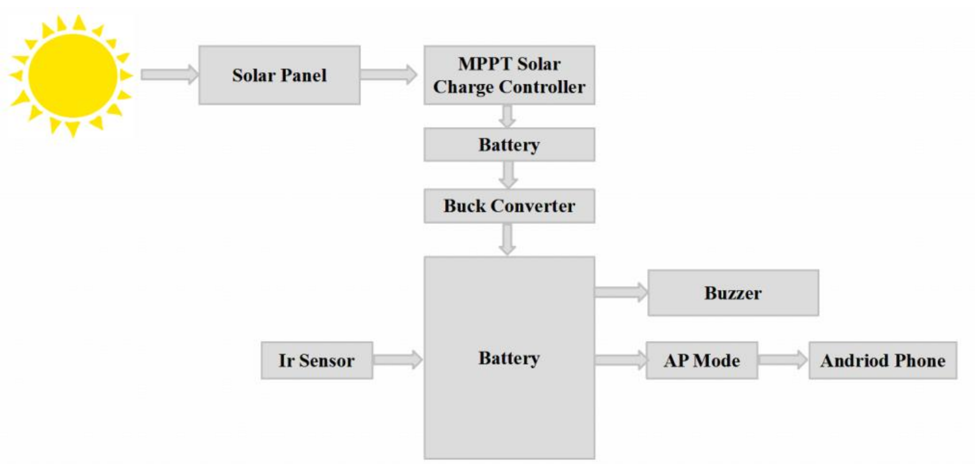


Figure 1. *System Architecture.*

4.2. Implementation Technique

Figure 2 illustrates the operational workflow of the proposed IoT-Based Smart Bus Stop with Energy Harvesting system. The process begins with the generation of electrical energy through the photovoltaic solar panel. When sunlight falls on the panel, it converts solar radiation into electrical power, which serves as the primary energy source of the system.

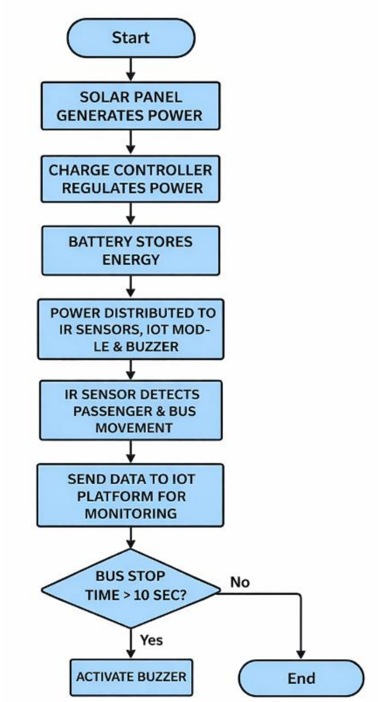
The generated energy is then passed through a Maximum Power Point Tracking (MPPT) charge controller. This controller regulates voltage and current levels to ensure optimal charging conditions while protecting the battery from overcharging, deep discharge, and voltage fluctuations. The regulated energy is stored in a rechargeable battery, which acts as a stable power reservoir and enables continuous operation even when sunlight is unavailable. Once energy is stored, power is distributed to the system components including the infrared sensors, IoT communication module (NodeMCU), and the buzzer. The IR sensors continuously monitor the bus stop environment by detecting passenger movement and bus presence. These sensors identify when passengers board or leave the bus and also detect bus arrival and departure events.

The collected sensor data is processed by the microcontroller and transmitted wirelessly to an IoT monitoring platform. This allows real-time visualization of parameters such as passenger count, bus activity, solar voltage, and battery status through a mobile or web interface. The communication system ensures remote monitoring and efficient management of the bus stop infrastructure. A decision-making stage is incorporated into the workflow to improve operational efficiency. The system evaluates how long a bus remains at the stop. If the dwell time exceeds a predefined threshold (10 seconds in this implementation), the system automatically activates the buzzer to alert the driver and passengers. This mechanism helps maintain discipline, reduce unnecessary delays, and improve traffic flow at bus stops. This flowchart demonstrates how renewable energy harvesting, sensor-based monitoring, embedded processing, and IoT communication work together to create a self-sustaining smart transportation solution. The automated workflow ensures energy-efficient operation, real-time data availability, and improved passenger management, which are essential features of modern smart city infrastructure.

Figure 2. *Implementation Technique*

4.3. System Diagram

The circuit diagram illustrates the electrical interconnection of all components within the proposed solar-powered IoT monitoring system. The photovoltaic solar panel serves as the primary energy source and is connected to an MPPT (Maximum Power Point Tracking) charge controller, which optimizes power extraction and regulates voltage and current to ensure efficient battery charging. The rechargeable battery functions as the main power reservoir, enabling continuous system operation even in the absence of sunlight. A DC–DC buck converter is incorporated to provide a stable and regulated voltage suitable for the microcontroller, sensors, and auxiliary components. The infrared (IR) sensor is interfaced with the control



circuit to detect passenger movement or bus presence. Upon detecting motion, the sensor sends a signal to the microcontroller, which processes the input and activates a buzzer to generate an audible alert when necessary.

The microcontroller is configured to operate in Access Point (AP) mode, allowing it to establish a wireless connection with an Android device or IoT platform. Through this connection, system data and alerts are transmitted in real time for monitoring and control. Since all components draw power from the battery charged by solar energy, the system is capable of autonomous and uninterrupted operation, making it suitable for sustainable smart transportation applications.

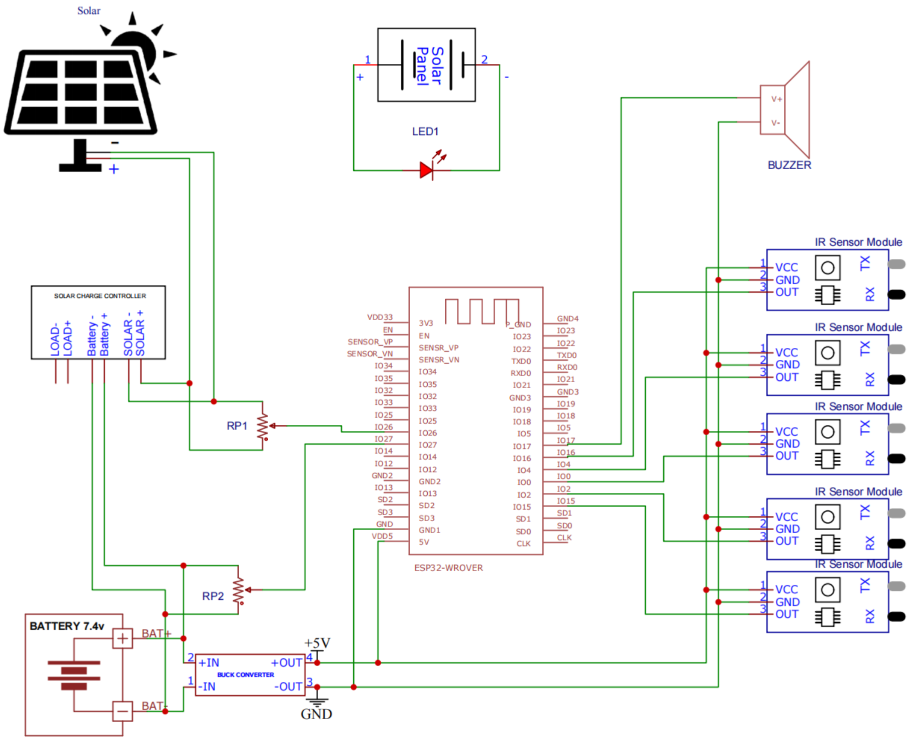


Figure 3. *System Implementation Diagram*

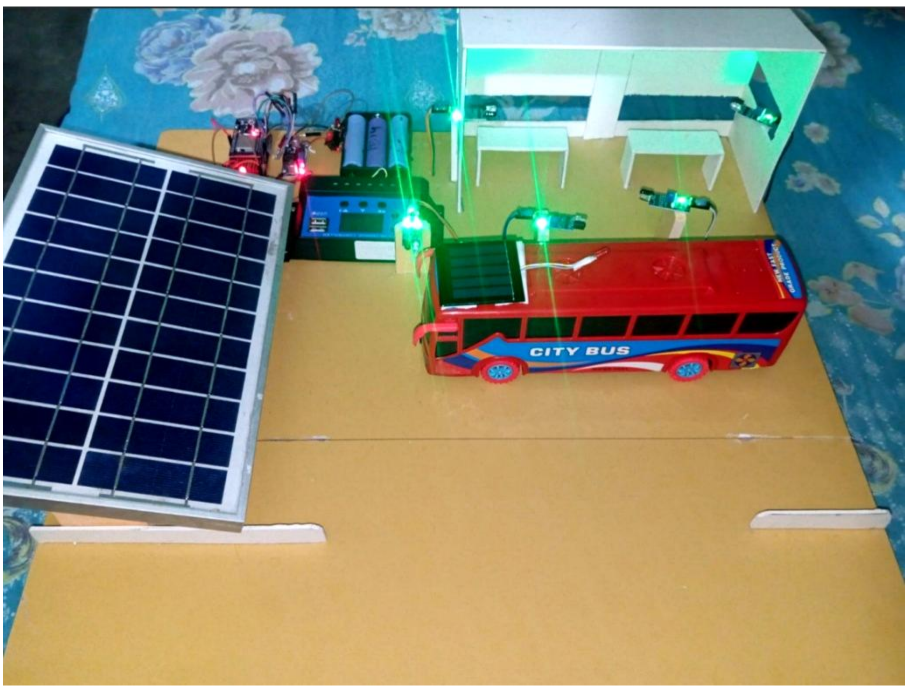


Figure 4. *System Implementation Diagram*

5. Result and Discussion

The developed IoT-based smart bus stop prototype was tested under real operating conditions to evaluate its performance in energy generation, sensing accuracy, data transmission, and overall system reliability. Experimental observations confirm that the system operates effectively as designed and meets the intended project objectives. During operation, the solar panel successfully generated sufficient electrical power to support the system. The MPPT charge controller maintained stable charging conditions and ensured efficient energy transfer to the battery. As a result, the system operated autonomously without relying on the main power grid, demonstrating its suitability for sustainable and off-grid transportation infrastructure. The infrared sensors performed reliably in detecting passenger movement. The system accurately counted passengers boarding, leaving, and waiting within the shelter, significantly reducing the possibility of manual counting errors. Bus arrival and departure events were detected in real time, allowing the system to track vehicle activity effectively. These results confirm that low-cost IR sensors can provide sufficient accuracy for crowd monitoring in smart bus stop applications. The IoT communication module successfully transmitted real-time operational data to the monitoring dashboard. Parameters including solar voltage, battery voltage, passenger count, and bus activity were displayed clearly on the interface, enabling remote monitoring and analysis. The wireless communication remained stable throughout testing, confirming the feasibility of cloud-based monitoring for transportation infrastructure management. The dwell-time monitoring feature functioned as intended. When a bus remained at the stop for more than the predefined threshold, the buzzer alert was triggered automatically. This functionality demonstrates the potential of the system to support operational discipline, reduce unnecessary delays, and improve traffic flow at bus stops.

Table 1. *Experimental Readings*

Test No.	Solar Voltage (V)	Battery Voltage (V)	Shed IN	Shed OUT	Shed Total	Bus IN	Bus OUT	Bus Total	Buzzer Triggered
1	2.58	12.00	0	0	0	5	5	0	No
2	2.39	12.00	5	5	0	5	5	0	No
3	2.62	12.05	3	1	2	4	2	2	No
4	2.71	12.10	6	2	4	3	1	2	Yes
5	2.45	11.98	2	0	2	6	3	3	No
6	2.30	11.92	4	1	3	2	0	2	Yes
7	2.18	11.85	1	1	0	7	4	3	No
8	2.75	12.15	5	3	2	5	2	3	Yes
9	2.82	12.20	8	4	4	3	1	2	No
10	2.50	12.05	2	1	1	4	4	0	No
11	2.33	11.90	3	3	0	2	1	1	Yes
12	2.60	12.08	6	2	4	6	5	1	No
13	2.40	11.96	4	4	0	3	3	0	No
14	2.72	12.18	7	2	5	5	2	3	Yes
15	2.55	12.10	3	0	3	4	1	3	No

The experimental results obtained from multiple test cases demonstrate that the proposed IoT-based smart bus stop system operates reliably under varying environmental and operational conditions. The solar energy harvesting unit showed consistent performance, with solar voltage readings ranging from approximately 2.18 V to 2.82 V depending on sunlight intensity. Despite fluctuations in solar input, the MPPT charge controller maintained stable battery voltage close to 12 V throughout the tests. This confirms that the energy management subsystem effectively regulates power flow and ensures uninterrupted system operation, validating the feasibility of using solar energy as the primary power source for smart transportation infrastructure. Passenger monitoring results indicate that the infrared sensors accurately detected passenger movement in both the bus and shelter areas. The recorded data reflected dynamic crowd behavior, including periods of low occupancy and instances of higher passenger flow. The system successfully tracked boarding and alighting activities without manual intervention, demonstrating its potential to reduce human error and improve passenger management efficiency. These findings highlight the suitability of low-cost IR sensors for real-time crowd detection in smart public transport systems. The IoT communication module consistently transmitted system data to the monitoring dashboard without interruption, allowing real-time visualization of energy status, passenger count, and bus activity. Stable wireless connectivity confirms that cloud-based monitoring can be effectively implemented for distributed transportation infrastructure. Such remote accessibility enables transport authorities to make informed operational decisions and respond promptly to system events. The dwell-time control mechanism also performed as expected. In test cases where the bus remained at the stop beyond the predefined threshold, the buzzer alert was triggered automatically. This demonstrates the ability of the system to enforce operational discipline, minimize congestion, and improve scheduling efficiency. The automated alert mechanism can contribute to smoother traffic flow and better time management at busy urban bus stops.

So, the results validate that integrating renewable energy harvesting with IoT-based monitoring and automated control creates a reliable, efficient, and scalable solution for smart transportation infrastructure. The system maintained stable power supply, accurate passenger detection, and effective communication throughout the experiments. These outcomes indicate that the proposed design can significantly enhance the functionality of traditional bus stops and support the development of sustainable smart city transport systems.

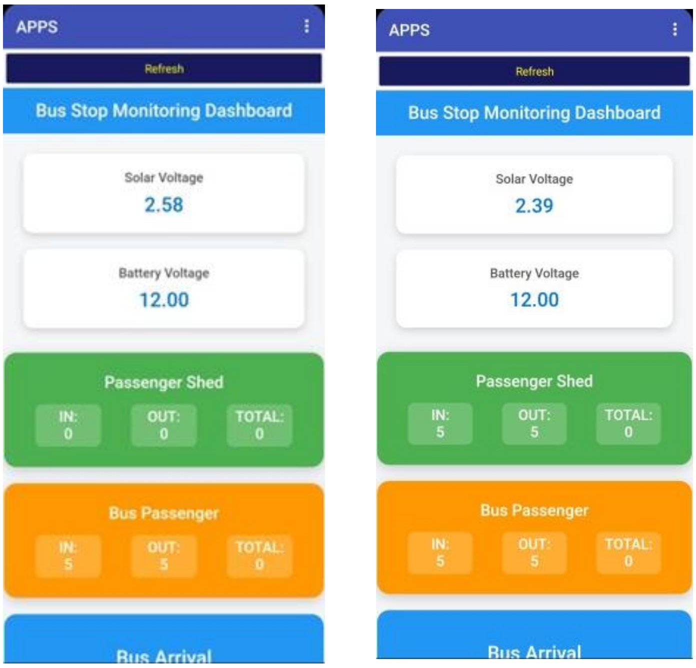


Figure 5. *Bus Stop Monitoring Dashboard (solar Voltage, Battery voltage and Bus passenger)*

6. Conclusion

This paper presented the design and implementation of a solar-powered IoT-based smart bus stop system aimed at improving the efficiency, sustainability, and automation of urban public transportation infrastructure. The proposed system integrates photovoltaic energy harvesting, MPPT-based power regulation, battery storage, sensor-based passenger monitoring, and wireless IoT communication into a unified platform. By utilizing renewable solar energy, the system operates independently from the grid, reducing operational costs and carbon footprint while ensuring continuous service availability. The implementation demonstrates that infrared sensors can effectively detect passenger movement, count boarding and alighting events, and monitor bus arrival and departure in real time. The NodeMCU-based controller successfully processes this data and transmits it to an IoT dashboard, enabling remote monitoring of bus activity, crowd density, battery voltage, and solar performance. The inclusion of a dwell-time monitoring mechanism with automated buzzer alerts improves operational discipline and minimizes unnecessary delays at bus stops. The experimental prototype confirms that the system is technically feasible, energy-efficient, and economically viable for deployment in smart city environments. Its modular design allows easy scalability and adaptation to different transportation infrastructures. The proposed solution contributes to sustainable urban mobility by enhancing passenger information services, optimizing energy utilization, and reducing manual monitoring requirements. Future work will focus on extending the system for large-scale deployment across multiple bus stops and integrating it with centralized traffic management platforms. Advanced data analytics and machine learning techniques can be incorporated to predict passenger demand, optimize bus scheduling, and improve route planning. Additional enhancements may include integration of environmental sensors, digital passenger information displays, and automated ticketing interfaces, further transforming traditional bus stops into intelligent smart city nodes.

Acknowledgements

The authors gratefully acknowledge the Department of Electrical and Electronic Engineering at Atish Dipankar University of Science and Technology (ADUST) for providing the laboratory facilities, equipment, and technical guidance required to conduct this research. Special thanks are extended to the EEE Lab staff for their assistance during system testing and implementation.

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