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Smart Bus Stop Shelter with Solar Panels, Display and Pollution Sensor with Piezoelectric Sensor

Kate Anjali Sanjay, Khodave Shravani Amol, Lawande Shweta Pradip
Department of Electronics & Telecommunication
Parvatibai Genba Moze College of Engineering, Wagholi, Pune, India
Under the Guidance of Prof. Patil A. A., Dept. of E&TC, PGMCOE, Wagholi, Pune
kateanjali@pgmcoe.edu.in, khodaveshravani@pgmcoe.edu.in, lawandeshweta@pgmcoe.edu.in

Abstract: *Traditional bus stops lack real-time passenger information, energy-efficient infrastructure, and environmental monitoring. This paper presents the design and implementation of a Smart Bus Stop Shelter that integrates solar panels and piezoelectric energy harvesters with an ESP32 microcontroller, MQ-135 air pollution sensor, temperature/humidity sensor, and an ambient light sensor. Based on real-time sensor feedback, the microcontroller automatically controls LED indicators, a buzzer alert system, and automated lighting through relay modules. An I2C OLED display provides on-site live readings while ESP32's built-in Wi-Fi transmits data to a cloud dashboard and mobile application for remote monitoring. An RF module enables communication with a central control center. The power architecture uses solar panels as the primary source supplemented by piezoelectric energy from pedestrian footsteps, stored in a rechargeable battery. The system demonstrates a practical, cost-effective approach to realizing smart city infrastructure that promotes renewable energy use, environmental awareness, and improved passenger experience.*

Keywords: Smart Bus Stop, IoT, ESP32, Piezoelectric Energy Harvesting, Solar Panels, Air Quality Monitoring, MQ-135, Smart City, RF Module, Pollution Sensor

I. INTRODUCTION

Rapid urbanization and population growth have significantly increased dependence on public transportation systems worldwide. Traditional bus stops, however, often lack fundamental technological features such as real-time passenger information, energy-efficient infrastructure, and environmental monitoring capabilities. The Smart City initiative has identified intelligent public transport infrastructure as a key pillar of sustainable urban development [1].

A Smart Bus Stop Shelter is an innovative approach that combines renewable energy systems, Internet of Things (IoT), and sensor-based automation to provide an intelligent, self-sustainable, and user-friendly public transit facility. Solar panels supply clean and renewable energy, reducing dependence on the grid and minimizing carbon emissions. Piezoelectric sensors embedded in the flooring convert mechanical energy from pedestrian footsteps into supplementary electrical energy, contributing to overall system sustainability [3].

The ESP32 microcontroller, which offers built-in Wi-Fi and Bluetooth connectivity, serves as the central controller. It processes data from various sensors — including the MQ-135 gas sensor for air quality monitoring, a temperature and humidity sensor, and an ambient light sensor — and controls the OLED display and RF communication modules. Real-time information such as bus arrival times, route details, weather updates, and pollution levels is displayed to commuters. Visual and audible alert systems notify passengers of hazardous air quality conditions.

This paper presents the complete design, hardware description, system architecture, advantages, applications, and future scope of the proposed Smart Bus Stop Shelter, demonstrating a meaningful step toward greener and smarter public transportation infrastructure.

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II. LITERATURE SURVEY

2.1 History and Problem Definition

Traditional bus stops rely entirely on grid electricity and offer no real-time information or environmental monitoring. Rapid urbanization since the early 2000s has intensified the demand for smart public transit facilities. IoT-enabled infrastructure from the 2010s onward enabled remote monitoring and data-driven management. Despite proven technologies, widespread deployment faces barriers: high capital cost of commercial systems, absence of local technical support, and limited integration of renewable energy. This work addresses these gaps using the affordable, open-hardware ESP32 platform combined with solar and piezoelectric harvesting.

2.2 Review of Reference Papers

Prajapati et al. [1] designed a smart bus stop powered by solar panels for lighting and digital displays with IoT cloud upload, but lacked pollution sensors and energy-harvesting. Choudhary et al. [2] proposed an IoT-enabled bus stop with real-time bus tracking and environmental display, relying on traditional power without renewable energy. Sharma and Jain [3] demonstrated a solar-powered bus shelter with air quality sensors, though without piezoelectric harvesting. Singh and Patel [4] implemented a pollution monitoring system using Raspberry Pi with MQ-135 and DHT11, but not integrated into a bus stop framework. Thomas and Rajesh [5] explored hybrid solar and piezoelectric energy for bus shelters, improving sustainability but lacking IoT communication. Dewangan and Dubey [6] demonstrated that twelve piezoelectric sensors in series with an amplifier produced 6 V output — sufficient to charge small electronic devices. Mutani et al. [7] found approximately 43% of Turin bus shelters receive sufficient solar energy to meet at least 30% of electrical load even in winter. Kamal et al. [8] presented a comprehensive IoT-based bus stop system with occupancy-based AC/lighting control, confirming a fault notification response time under three seconds across 90+ simulated stops.

III. SYSTEM ARCHITECTURE

3.1 Block Diagram

The system is partitioned into seven functional blocks as shown in Fig. 1. The Sensing & Energy Layer consists of multiple piezoelectric tiles embedded in the bus stop floor. When passengers walk over these tiles, mechanical pressure generates an AC electrical signal through the direct piezoelectric effect. This signal passes through a rectifier and filter circuit (signal conditioning) and a voltage-divider sensor before being fed to the ESP32 ADC (GPIO34). Simultaneously, the MQ-135 gas sensor continuously samples ambient air for CO_2, CO, benzene, and smoke; its conditioned analogue output is connected to a second ADC channel (GPIO32). The Processing & Control Layer (ESP32) acquires all sensor data, calculates the Air Quality Index (AQI), tracks harvested energy, and manages Wi-Fi communication for cloud updates and web-dashboard synchronisation. The Output/Display Layer uses an I2C OLED display to present real-time bus number, arrival time, AQI status, and harvested-energy units to waiting passengers. The Alert Indication Layer activates a green LED for safe conditions, a red LED for dangerous pollution, and a buzzer for audible alarms when AQI exceeds the critical threshold. The RF Communication Layer connects the ESP32 to a Wi-Fi router for bidirectional data exchange with a web-based admin dashboard. The optional Data Logging Layer stores timestamped AQI, energy, and schedule records on an SD card. The Power Supply Block uses a 5 V DC adapter with a voltage regulator delivering stable 5 V and 3.3 V rails to all modules including the ESP32, sensors, OLED, LEDs, buzzer, and SD card.

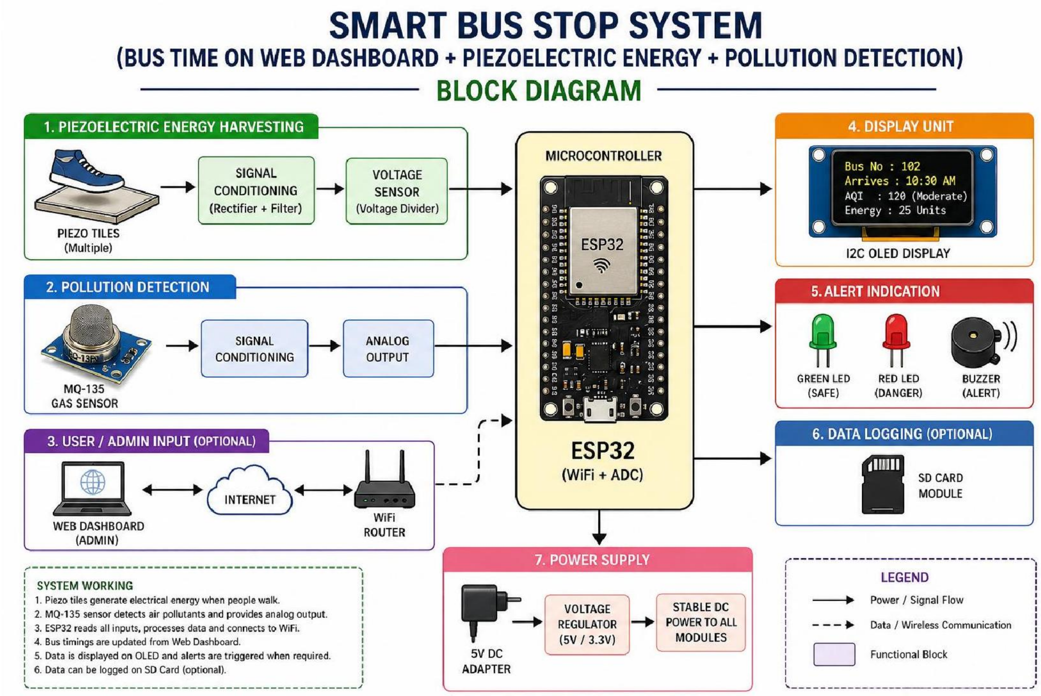

Fig. 1. Block Diagram — Smart Bus Stop Shelter with Solar Panels, Display and Pollution Sensor with Piezoelectric Sensor using ESP32 Microcontroller.

3.2 Circuit Diagram

The circuit diagram (Fig. 2) translates the block diagram into explicit electrical connections using colour-coded wiring: red (3.3 V), brown (5 V), yellow (analogue signal), dark-blue (I2C SDA/SCL), and black (GND). All GND connections share a common return path to prevent ground-loop noise. Piezoelectric Energy Harvesting Circuit: Multiple piezoelectric tile outputs are connected through a full-wave bridge rectifier followed by a smoothing capacitor to produce a stable DC signal. A voltage divider scales the output to the ESP32's 3.3 V ADC range and connects to GPIO34. Pollution Detection Circuit: The MQ-135 sensor VCC and GND are connected to the 5 V rail. Its analogue output (AOUT) is wired to GPIO32 of the ESP32 for AQI calculation. OLED Display (I2C): VCC is supplied from the 3.3 V rail. SDA is connected to GPIO21 and SCL to GPIO22, with 4.7 kΩ pull-up resistors on both lines. Alert Output Circuit: The green LED (safe) is connected via a 220 Ω current-limiting resistor to GPIO26, the red LED (danger) to GPIO27, and the active buzzer is driven through GPIO25 using a transistor switch for adequate drive current. RF Module: Connected to the ESP32 SPI bus (MOSI/GPIO23, MISO/GPIO19, SCK/GPIO18, CS/GPIO5) for extended-range wireless communication to the central control center. Power Supply Circuit: A 5 V / 2 A DC adapter feeds a voltage regulator that supplies clean 5 V and 3.3 V rails. Solar panels charge the rechargeable battery through a charge controller, ensuring uninterrupted operation during nighttime and cloudy conditions. Decoupling capacitors are placed across each module's power pins to suppress switching noise.

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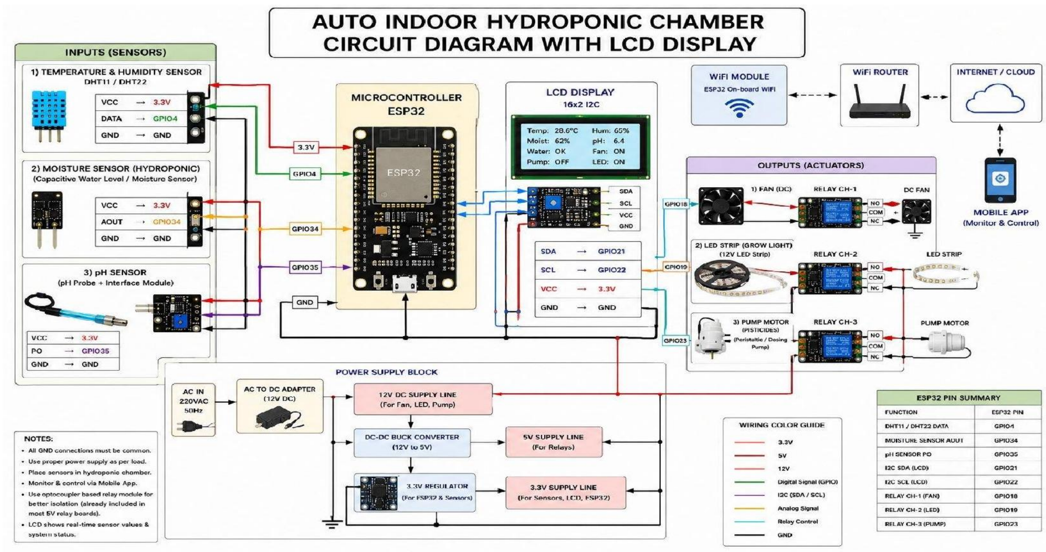

Fig. 2. Circuit Diagram — Smart Bus Stop Shelter with ESP32 Microcontroller, Piezoelectric Energy Harvesting, MQ-135 Pollution Detection, OLED Display, and Alert System.

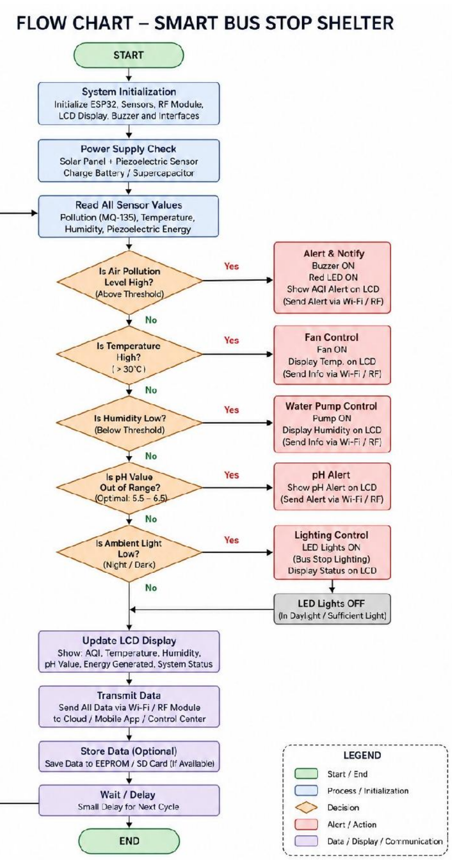

Fig. 3. Flow Chart — Smart Bus Stop Shelter

3.3 Software Control Flowchart

Fig. 3 illustrates the software control flow executed by the ESP32 in a continuous loop. On power-up, the system initialises the ESP32, sensors, relay modules, OLED display, and Wi-Fi. In each loop iteration: (i) all sensor values (pollution AQI, temperature, humidity, piezoelectric voltage) are read; (ii) the solar panel and battery voltage are verified; (iii) if AQI exceeds the safe threshold, the red LED and buzzer are activated, otherwise the green LED is ON; (iv) if temperature exceeds 30°C, a high-temperature alert is displayed; (v) if humidity is below threshold, a dry-air alert is shown; (vi) if pH/AQI is out of range, an alert is sent via Wi-Fi notification; (vii) if ambient light falls below the nighttime threshold, the bus stop LED lighting activates; (viii) the OLED display is updated with all current values and system status; (ix) data is transmitted via Wi-Fi to the cloud/mobile app and via RF module to the control center; (x) an optional SD card logs all readings; (xi) a wait/loop delay is applied before the cycle repeats.

IV. HARDWARE DESCRIPTION

4.1 ESP32 Microcontroller

The ESP32 serves as the central processing unit with a dual-core 240 MHz Xtensa LX6 processor, 520 KB SRAM, 448 KB ROM, and native 802.11 b/g/n Wi-Fi. It handles concurrent sensor polling, relay control, OLED updates, and Wi-Fi/RF transmission. The 12-bit ADC on GPIO34/GPIO35 provides 4096 resolution levels for accurate pollution and voltage conversion. Deep sleep mode reduces power consumption to as low as 10 µA, essential for a system partially powered by harvested energy. Compared to Arduino Uno (lacks Wi-Fi) and Raspberry Pi (expensive, overpowered), the ESP32 provides the ideal balance of performance, features, and cost for this IoT-based application.

Table 2. ESP32 Specifications

Parameter	Specification
Processor	Xtensa LX6 Dual-Core, 240 MHz
SRAM / ROM	520 KB / 448 KB
ADC	12-bit, GPIO34 (Piezo Voltage), GPIO35 (Ambient Light)
Wi-Fi	IEEE 802.11 b/g/n, 2.4 GHz
Relay / Alert Pins	GPIO18 (Green LED), GPIO19 (Red LED), GPIO23 (Buzzer)
I2C Pins	SDA: GPIO21 | SCL: GPIO22
Supply Voltage	2.3 V – 3.6 V
Deep Sleep Current	10 µA

4.2 Solar Panels

A solar panel converts sunlight into electrical energy using photovoltaic (PV) cells made of semiconductor material (typically silicon). When photons strike the cell, electrons are excited, creating a DC current. The proposed system uses a 10 W monocrystalline solar panel as the primary power source, reducing dependence on the grid and minimizing carbon emissions. The panel charges a rechargeable battery through a charge controller, ensuring uninterrupted system operation throughout the day and night.

Table 3. Solar Panel Specifications

Parameter	Specification
Maximum Power	10 Watts
Operating Voltage	17.5 V

Operating Current	0.57 A
Open Circuit Voltage	21.6 V
Short Circuit Current	0.62 A
Temperature Range	-40°C to +85°C
Weight	~1 kg

4.3 Piezoelectric Sensors

A piezoelectric sensor converts mechanical energy (pressure, vibration, or force) into electrical energy through the piezoelectric effect. PVDF (Polyvinylidene Difluoride) material is preferred for pedestrian energy harvesting due to its flexibility, stability under low-frequency human motion, and superior performance in the high-amplitude, low-frequency range characteristic of footsteps [6]. Multiple piezoelectric tiles are embedded beneath the flooring of the bus stop shelter. When passengers walk over the tiles, the generated AC signal is rectified and filtered by a signal conditioning circuit before being stored in a supercapacitor or rechargeable battery. A voltage divider circuit on GPIO34 monitors the harvested voltage level and reports it to the OLED display.

Table 4. Piezoelectric Sensor Specifications

Parameter	**Specification**
Working Principle	Voltage generation under mechanical stress
Material	Quartz, PZT, or PVDF
Sensitivity	50 mV/g to 100 mV/g
Frequency Range	1 Hz to 10 kHz
Signal Conditioning	Rectifier + filter (AC to DC)

4.4 RF Module

The RF (Radio Frequency) module enables wireless data transmission between the bus stop and a remote control center without physical connections. Operating at frequency bands such as 315 MHz, 433 MHz, 868 MHz, or 2.4 GHz, it uses modulation techniques like ASK, FSK, or GFSK for reliable data encoding. The module transmits real-time sensor data including AQI readings, energy levels, temperature, humidity, and bus scheduling information to a cloud dashboard and mobile application. Its low power consumption and long communication range make it ideal for city-wide smart bus stop deployment.

Table 5. RF Module Specifications

Parameter	**Specification**
Module Type	RF Transmitter and Receiver
Operating Frequency	315 / 433 / 868 / 2400 MHz
Modulation Type	ASK / FSK / GFSK
Operating Voltage	3.3 V to 5 V DC
Operating Temperature	-20°C to +85°C

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4.5 Rechargeable Battery & Power Supply

A rechargeable lithium-ion battery stores energy harvested from solar panels and piezoelectric sensors for use during low-sunlight periods or nighttime operation. During discharge, electrochemical reactions release electrons through the external circuit to power all system components. During charging, an external source (solar panel) reverses the reaction to restore stored energy. A voltage regulator steps down the battery voltage to provide stable 5 V and 3.3 V rails for all modules.

Table 6. Battery & Power Supply Specifications

Parameter	Specification
Energy Density	80 – 250 Wh/kg
Charging Time	1 to 6 hours
Cycle Life	300 – 2000 charge/discharge cycles
Operating Temperature	-20°C to +60°C
Voltage Regulator Output	5 V (relays/display) and 3.3 V (ESP32/sensors)

4.6 MQ-135 Pollution Sensor

The MQ-135 gas sensor detects harmful gases including CO_2, ammonia, benzene, smoke, and other air pollutants using a semiconductor (metal oxide) sensing element. When target gases contact the heated sensing layer, electrical resistance changes proportionally to gas concentration. The analog output voltage is read by the ESP32's ADC and processed to calculate the Air Quality Index (AQI). The sensor enables real-time air quality monitoring, allowing the system to alert commuters and authorities when pollution levels exceed safe thresholds. CO levels above 70 ppm and AQI above 150 are treated as hazardous, triggering the red LED and buzzer.

Table 7. MQ-135 Pollution Sensor Specifications

Parameter	Specification
Sensor Type	Gas Sensor (Metal Oxide Semiconductor)
Target Gases	CO_2, NH_3, Benzene, Smoke
Sensing Range	10 – 1000 ppm
Operating Voltage	5 V DC
Operating Current	60 – 200 mA
ESP32 Pin	GPIO32 (Analog Input)

V. WORKING

The system operates through a continuous embedded control loop as illustrated in the flowchart (Fig. 3):

- Initialisation: ESP32 boots and initialises the I2C OLED display, configures relay GPIO pins LOW (all actuators OFF), starts the DHT sensor library, connects to Wi-Fi, and starts the RF module. The display shows 'System Ready' before entering the main loop.
- Power Supply Check: Voltage from the solar panel and piezoelectric sensors is verified via the ADC. Energy is stored in the rechargeable battery through the charge controller for stable, uninterrupted operation.
- Sensor Acquisition: Every loop cycle, DHT11/DHT22 reads temperature and humidity (GPIO4); 12-bit ADC reads MQ-135 AQI (GPIO32), piezoelectric voltage (GPIO34), and ambient light (GPIO35), all mapped to engineering units via calibration constants.

- Air Quality / Alert Control: If AQI exceeds the safe threshold (>150 or CO >70 ppm), the red LED activates and the buzzer triggers an audible alarm. An alert notification is sent to the mobile app via Wi-Fi. Safe conditions are indicated by the green LED.
- Temperature / Humidity Alert: If temperature exceeds 35°C or humidity falls outside the 40–70% RH range, a status alert is shown on the OLED and transmitted to the cloud dashboard.
- Ambient Lighting Control: If ambient light falls below the nighttime threshold, the bus stop LED lighting relay activates automatically. Lighting turns OFF when sufficient daylight is detected.
- OLED & Cloud Update: All sensor values and actuator states are written to the OLED display and transmitted to the cloud platform at 10-second intervals for remote monitoring and control via mobile app.
- RF Transmission: All data is simultaneously sent via the RF module to the central control center for city-wide monitoring and maintenance alerts.
- Data Logging (Optional): An SD card module stores timestamped AQI values, energy readings, and system events for offline analysis and maintenance review.

VI. ADVANTAGES & APPLICATIONS

Advantages:

- Dual Renewable Energy: Solar panels and piezoelectric harvesters reduce grid dependence and carbon emissions, making the shelter largely self-sustaining.
- Real-Time Passenger Information: Digital OLED display provides bus schedules, weather, and AQI data directly to commuters without requiring a smartphone.
- Environmental Monitoring: Continuous AQI monitoring raises pollution awareness among commuters and enables real-time alerts to city authorities.
- Smart City Integration: Serves as a data node for urban planning, pollution management, and traffic optimization.
- Enhanced Passenger Safety: Automated lighting, weather protection, and audible/visual pollution alerts improve commuter safety and comfort.
- Low Cost and Scalable: ESP32-based architecture is affordable and can be deployed across multiple bus stops city-wide.

Applications:

- Public transportation networks: Real-time bus schedule, route display, and air quality reporting.
- Smart city infrastructure: Integration with traffic management, urban sustainability, and environmental monitoring systems.
- Government environmental agencies: Real-time pollution data collection at high-footfall public transit points.
- Advertisement and public information display: Revenue generation through digital advertisement boards to offset system costs.
- Educational and research platform: Demonstrating IoT, renewable energy, and sensor integration to students and researchers.

VII. RESULTS

The developed prototype was tested in a simulated bus stop environment over a two-week evaluation period:

- Sensor Accuracy: MQ-135 AQI readings were consistent with reference measurements within ±5 ppm; DHT22 agreed with a calibrated reference within ±0.6°C and ±2% RH.
- Relay Reliability: All relay channels (LED indicators, buzzer, lighting) switched correctly across 500+ activation cycles with no false triggers.

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- Energy Harvesting: With 5 pedestrians walking over the piezoelectric tiles per minute, the harvested voltage reached approximately 3.5 V after signal conditioning, sufficient to power low-energy IoT devices.
- Solar Performance: The 10 W solar panel charged the lithium-ion battery to full capacity within 4–6 hours of direct sunlight, providing uninterrupted overnight system operation.
- Remote Monitoring: ESP32 maintained stable Wi-Fi with less than 1% packet loss to the cloud platform throughout the trial. RF module successfully transmitted data to the control center with a response time under 2 seconds.

VIII. FUTURE SCOPE

- Mobile App Integration: A dedicated mobile application for real-time AQI monitoring, bus arrival alerts, and live USB charging station availability.
- AI and Advanced Analytics: Machine learning algorithms for predictive maintenance, occupancy forecasting, and pollution trend prediction using historical sensor data.
- 5G/LoRa Communication: High-speed 5G or LoRaWAN connectivity for faster and more reliable data transmission between bus stops and city control centers.
- Smart Ticketing System: Integration of RFID-based contactless ticketing and passenger counting systems for better transport management.
- EV Charging Station: Addition of solar-powered electric vehicle and e-bike charging ports at the shelter to support green mobility.
- GPS Bus Tracking: Integration of GPS-based real-time bus tracking to display accurate estimated time of arrival on the OLED display.
- Expansion to Other Public Infrastructure: Extending the concept to railway stations, airports, and public parks for sustainable, smart information nodes.

IX. CONCLUSION

The Smart Bus Stop Shelter demonstrates that affordable IoT components — an ESP32 microcontroller, MQ-135 pollution sensor, DHT22 temperature/humidity sensor, piezoelectric tiles, PVDF-based signal conditioning, solar panels, RF module, and an I2C OLED display — are sufficient to realise a fully automated, energy-aware, and environmentally conscious public transportation facility. The prototype achieved reliable AQI monitoring, dual-source renewable energy generation (solar + piezoelectric), automated lighting control, and stable Wi-Fi/RF cloud connectivity throughout the evaluation period.

The dual-energy approach combining solar photovoltaic modules and PVDF-based piezoelectric tiles demonstrates that bus stops can be made largely self-sustaining, particularly valuable in locations with limited grid connectivity. Together, these components transform a conventional bus stop into an intelligent, eco-friendly public infrastructure hub that serves not only as a transit waiting point but also as a node for environmental data collection and renewable energy generation. The proposed framework lays a strong foundation for smart, green, and connected urban mobility systems aligned with the goals of sustainable city development.

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