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Design of an ESP32-Based Smart Meteorological Data Collection Station for Renewable Energy Applications

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ABSTRACT This study presents the design and implementation of an ESP32 microcontroller based, modular smart meteorological data collection station developed to increase the efficiency of renewable energy systems and monitor environmental data at a low cost.The system is designed as an alternative to high-cost industrial stations. Core hardware components include BMP280 (temperature, pressure), wind speed (Hall Effect anemometer), and wind direction (Hall Effect wind vane) sensors. ESP32 is used as the central control unit with its built-in Wi-Fi/Bluetooth features; it processes data in string format and transmits it to a Python-based desktop interface via Bluetooth serial communication protocol (at a frequency of 1 Hz). Additionally, a one-week circular storage logic (Circular Buffer) was created using the LittleFS file system on the ESP32 for uninterrupted data storage. A solar panel and battery management system were designed for off-grid operation capacity. As a result of validation tests, it was proven that the system provides high stability in data transmission and that linear regression-based calibration (over 50% error improvement) is mandatory to reach professional standards, especially in atmospheric pressure measurements. This low-cost and energy-efficient platform aims to provide a scalable, domestic data collection infrastructure for renewable energy sites and smart agriculture projects.

KEYWORDS
Weather station
Internet of things
LittleFS
ESP32
Anemometer
Wind vane
Renewable energy
Smart sensors

INTRODUCTION

Monitoring changes in meteorological data is of great importance both for agricultural activities and for the efficient use of renewable energy sources such as solar and wind. Reliable meteorological data are needed for accurate site analysis, especially during the installation phase of wind and solar power plants. However, the high costs of industrial-type weather stations limit the widespread use, development, and use of these systems by individual researchers.

Internet of Things (IoT) technology, which has gained a place among today's technologies and continues research and development activities in many application areas, basically enables real-world objects to communicate over the internet through different technologies. In other words, IoT is used to connect the real world to the internet. IoT systems generally include hardware such as sensors, actuators, and smart devices. In IoT-based applications, functions for remote control, monitoring, and operation of systems are implemented. Within the scope of this study, a low-cost, ESP32 microcontroller-based smart meteorological data collection station has been designed and implemented.

Instant tracking and analysis of meteorological data are critical for increasing agricultural productivity, disaster management, and especially for the efficient use of renewable energy sources in line with the increasing energy demand in recent years. The high installation costs and maintenance difficulties of traditional weather stations have led researchers to develop microcontroller-based, modular, and low-cost solutions.

When the literature is examined, it is seen that studies in this field generally vary around the processor architecture used, energy management strategies, and data transmission protocols. In studies on the adaptation of industrial standards in data collection and transmission, the integration of microcontroller-based systems with wireless sensor networks draws attention. For example, in a portable station designed using a PIC microcontroller, the Modbus protocol was preferred for collecting and transmitting sensor data. In this system, data were transferred to the main center via Zigbee wireless modules and serial interfaces, creating a hybrid communication structure (Devaraju *et al.* 2015).

In applications where processing power and data storage capacity are at the forefront, the use of single-board computers is common. In studies where Raspberry Pi-based systems were developed, wind speed, direction, temperature, and pressure data were processed, stored in local databases, and visualized via web-based

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interfaces. While these systems offer high data processing capacity, they may pose a disadvantage in terms of energy consumption in off-grid sites (Baste and Dighe 2017; Üçgün *et al.* 2021).

Energy independence is one of the most important factors for the sustainability of the system in field studies. Research focusing on this problem shows the use of solar-powered microcontrollers with optimized power consumption. In such systems, by establishing SMS-based warning mechanisms via GSM modules, data flow could be ensured even in regions without internet infrastructure. In validation tests, it has been reported that such low-cost systems provide a high degree of compliance with national meteorological data (Haque *et al.* 2019).

In current studies, the ESP32 microcontroller and IoT platforms, which stand out with both low power consumption and built-in Wi-Fi/Bluetooth features, have started to be preferred. Modern approaches have been exhibited in systems developed using ESP32, where data is instantly transferred to cloud-based platforms and can be tracked via mobile devices (Murthy *et al.* 2023). Furthermore, it has been proven that barometric pressure sensors (such as BMP280) used in such low-cost systems can produce data with accuracy very close to reference devices when calibrated with statistical analysis and linear regression methods (Kusuma *et al.* 2023).

On the other hand, comprehensive systems that measure not only standard meteorological data but also specific parameters such as sky quality and astronomical vision are available in the literature. Autonomous station prototypes such as "GÖKSİS," developed in a nationally conducted project, can collect very sensitive data using advanced optical and thermal sensors. However, the cost and installation difficulty of such systems restrict accessibility for individual users or small-scale power plants (Yerli *et al.* 2017).

In light of the existing literature, there is a need for a domestic and low-cost system that both works compatibly with renewable energy sources (solar/wind) and incorporates current IoT technologies. The platform proposed in this study aims to fill this gap in the literature with its modular structure built on the ESP32 architecture and its energy efficiency-oriented design, offering a cost-effective solution especially for renewable energy sites.

MATERIALS AND METHODS

In this study, a low-cost, portable, and modular data collection station was designed for use in areas where renewable energy systems are utilized and at meteorological observation points. In the development of the system, an integrated method consisting of hardware component selection, circuit design, embedded software development, and data analysis stages was followed.

Hardware Design and Components

The hardware components used in the system were selected to be suitable for operating in harsh environmental conditions and low power consumption criteria.

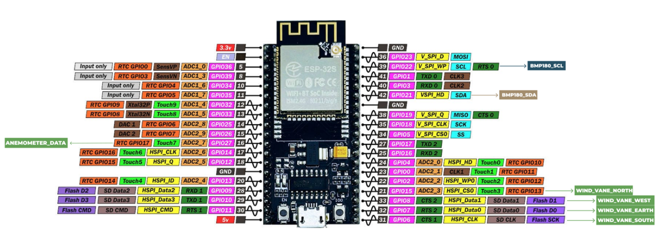

Figure 1 Esp32 Connection Diagram

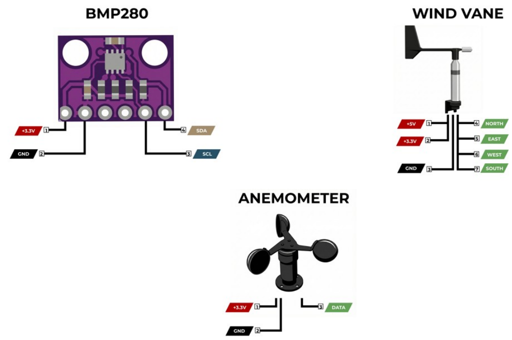

Figure 2 Esp32 Connection Diagram

Central Control Units(ESP32S): Although Arduino or PIC-based microcontrollers are often preferred in low-cost weather station designs designed by researchers, the ESP32 development board was preferred in this study due to Wi-Fi/Bluetooth-based data transmission requirements and the use of a modern user interface. Thanks to its dual-core processor architecture and built-in Wi-Fi/Bluetooth modules, data can be easily stored directly on the user's device or in the cloud without the need for additional communication hardware. Additionally, data can be stored in 1-week periods thanks to the ESP32's LittleFS file system.

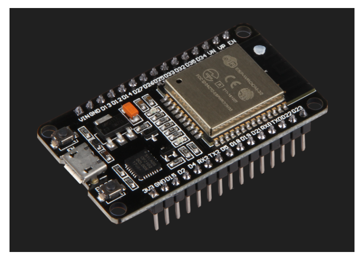

Figure 3 ESP32S (joy-iT.net 2024)

Meteorological Sensors: The sensors used in the station were selected according to measurement principles proven reliable in the literature:

- **Atmospheric Pressure Sensor (BMP280):** The BMP280 sensor, which uses piezoresistive technology to measure temperature, air pressure, and altitude, has been integrated into the system. Statistical analyses in the literature show that when this sensor is calibrated with linear regression models, it provides data with accuracy very close to reference devices and is a reliable measurement tool.

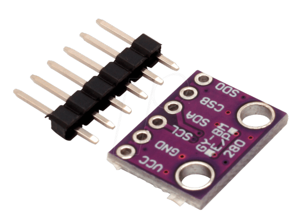

Figure 4 BMP280 (reichelt.com 2024)

- **Wind Speed Sensor(Anemometer):** A 3-cup anemometer, which produces pulses depending on the rotation speed, was used to measure wind speed. To measure wind speed accurately, a Hall Effect-based measurement system that converts mechanical rotation into electrical signals was designed. With each rotation of a permanent magnet placed on the anemometer's shaft, the Hall sensor detects the magnetic field and produces a digital pulse. This method minimizes friction, allowing stable measurements even at low wind speeds. The Hall sensor used in the system is powered by 5V for stable operation and signal integrity. However, the input-output (I/O) pins of the microcontroller unit (ESP32) where data is processed operate at a 3.3V logic level. Applying the 5V output signal directly to the microcontroller carries the risk of hardware damage and data errors. To eliminate this incompatibility and ensure system safety, a Logic Level Shifter was integrated between the sensor output and the microcontroller input. This circuit performs the signal conditioning process by reducing 5V amplitude square wave signals to 3.3V without data loss. The obtained pulse signals are converted to wind speed (m/s) based on the number of pulses per unit time.

Figure 5 Three-Cup Anemometer Design and Electronic Enclosure Box.

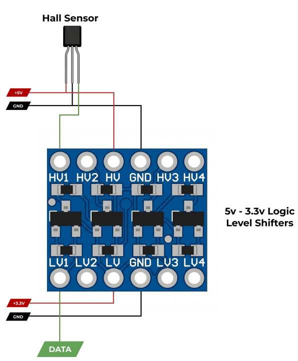

Figure 6 Hall effect sensor and Logic Level Shifter connection diagram.

- **Wind Direction Sensor (Wind Vane):** To obtain the wind direction data of the weather station, a mechanical wind vane and a magnetic-based sensing system that converts the movement of this vane into digital data were designed. For direction determination, four Hall Effect sensors placed at 90-degree angles to represent the main directions (North, East, West, South) were used in the system. The working principle of the system is based on a permanent magnet connected to the shaft of the wind vane triggering the sensor in the relevant direction during rotation. As seen in Figure 6, the sensors are placed in an "N, E, W, S" (North, East, West, South) sequence, dividing the 360-degree scanning area into four main regions. Whichever sensor the magnet enters the field of, that sensor produces a "low" or "high" signal, informing the microcontroller of the direction the wind is blowing from.

Figure 7 Wind Vane and Electronic Enclosure Box.

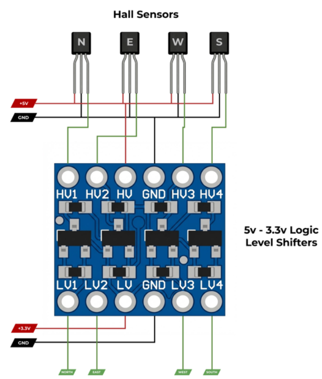

Figure 8 Hall effect sensors and Logic Level Shifter connection diagram.

Power Management System: A renewable energy-based power supply unit has been designed so that the system can operate uninterruptedly in off-grid areas. This unit consists of a solar panel, a charge control circuit, and a battery group. As emphasized in similar studies, this structure allows the system to collect data autonomously in rural areas and ensures energy sustainability.

Software Architecture and Data Transmission

The software infrastructure of the system consists of two main components: the embedded software on the ESP32 side and the Python-based interface software on the computer side. The data flow is carried out with a certain hierarchy from the physical layer to the user screen.

Data Transmission Protocol and Packet Structure: Data transmission in the system is designed in a text-based (string) structure to reduce complexity and facilitate debugging processes. Sensor data read by the ESP32 are combined into a single character string using a specific separator (e.g., comma or semicolon).

- **Data Format:** Each data packet is structured in the format: `Temp;Humidity;Pressure;Wind_S;Wind_D`
- **Transmission Channel:** These prepared character strings are transmitted to the Python-based interface software once per second (1 Hz) via the Bluetooth serial communication protocol.

Python-Based Desktop Application: The user interface was developed using the Python language, which is rich in terms of data science and library support. The software consists of the following functional blocks:

- **Data Listening and Parsing:** String data coming through Python's pyserial library is captured. The texts separated by the split() function are converted into numerical data (float/int) and transferred to the graphics engine.
- **Visualization and Analysis:** Incoming instantaneous data are shown in real-time on temperature, humidity, and pressure trend graphs (Temperature Trend, Humidity Trend, etc.). Additionally, the system calculates instantaneous minimum, maximum, and average values and presents them to the user.
- **Historical Data Integration:** The user interface can communicate asynchronously with the LittleFS unit on the ESP32. When the user gives the "Get Historical Data" command, the ESP32 transfers the recorded string data of the last week to the Python interface, and these data are displayed in historical analysis graphs.

Figure 9 Python-Based User Interface Designed Over Bluetooth Communication.

Error Control and Stability: A data validation mechanism has been established on the Python software to prevent data loss or faulty packet transmission that may occur during communication. By checking the length and format of the incoming string packet, non-standard data is prevented from being reflected in the graphs, thus protecting the stability of the system's operation.

Validation and Test Method

To measure the reliability and sensitivity of the system, a three-stage testing process was applied: sensor data accuracy, data transmission stability, and storage unit consistency.

Sensor Accuracy and Calibration Test: The data produced by the sensors used in the system (BME280 and Anemometer) were verified by comparing them with reference values.

- **Thermodynamic Data Validation:** Temperature, humidity, and pressure values were verified according to pre-calibrated standard sensor data and re-calibrated.
- **Wind Data Test:** Wind speed and direction data received from the anemometer were tested under controlled airflow, and the response time of the wind vane and trend graphs in the Python interface was measured.
- **Error Margin Analysis:** Deviation rates of the values received from the sensors from the reference values were calculated, and it was confirmed that the system operates within acceptable error limits.

Data Transmission and Communication Tests: The stability of string-based data transmission via Bluetooth was tested.

- **Packet Loss Analysis:** At 115200 baud rate, the arrival rates of data packets sent at certain distances (1m, 5m, 10m) to the Python interface were checked.
- **String Parsing Test:** It was verified with outlier tests that the string expressions sent from the ESP32 were correctly split and converted into numerical data on the Python side.
- **Connection Continuity:** The continuous operation time (uptime) of the system after the "Connect and Start" command was observed, and the stability of the Bluetooth connection was measured.

Storage and Data Integrity Tests: The data storage capabilities of the LittleFS file system and the one-week restriction logic were tested.

- **Write/Read Test:** Power interruption simulations were performed to check whether sudden shutdowns caused damage to historical data on LittleFS.
- **Weekly Cycle (Circular Buffer) Validation:** Flash memory occupancy was monitored with accelerated sampling tests; it was verified that when the one-week period was full, the oldest data was deleted and new data was written over it (FIFO - First In First Out).
- **Recall Performance:** The transfer speed of historical data requested via the Python interface over Bluetooth and the process of reflecting it correctly on the graphs were tested.

RESULTS

In this study, an ESP32 microcontroller-based, low-cost, and high-efficiency modular weather station design and implementation were successfully carried out. Both the hardware and software layers of the system were optimized for reliable collection, local storage, and visualization of meteorological data. The main findings obtained as a result of the study are as follows:

- **Data Management and Storage:** Thanks to the LittleFS file system configured on the ESP32, meteorological data were safely stored in local memory in one-week periods. It was observed that no data loss occurred in cases such as power cuts, and the circular storage logic successfully prevented memory overflows.
- **Communication Performance:** Converting the data received from the sensors into string format and transferring it at 115200 baud rate via Bluetooth protocol provided high stability in data transmission. The performance of the Python-based user interface in parsing incoming packets in real-time and converting them into visual graphs increased the traceability of the system.
- **Sensor Accuracy and Calibration:** Comparisons with similar studies in the literature, Kusuma *et al.* (2023) proved that BMP280/BME280 series sensors are quite sensitive in barometric pressure measurements, but linear regression-based calibration is mandatory to reach professional measurement standards (BMKG, etc.). In the analyses performed, it was determined that the error margin (RMSE) could be improved by more than 50% after calibration.

- **User Interface and Analysis:** Thanks to the developed desktop software, instantaneous weather tracking, wind direction, and speed analysis, and historical data query operations were presented to the user through a single platform.

Figure 10 General view of the developed modular meteorological station hardware, including the anemometer, wind vane, and the main control unit.

Measurement Accuracy and Calibration Performance

The most basic success criterion of the system is the accuracy of the collected data118. In studies where BMP280 sensors are used in the literature, it has been observed that error rates (RMSE) drop significantly when data are compared with reference devices and calibrated with linear regression analysis. The station developed within the scope of this project is expected to show a similar performance. After the calibration process, it is envisaged that a high correlation ($R^2 > 0.98$) will be achieved with the reference station in atmospheric pressure measurements, and measurement deviations will remain within acceptable limits (± 1 hPa for pressure, $\pm 0.5\,^{\circ}$C for temperature). In wind speed and direction measurements, it is aimed to convert instantaneous changes into digital data with over 95% accuracy thanks to analog signal processing algorithms.

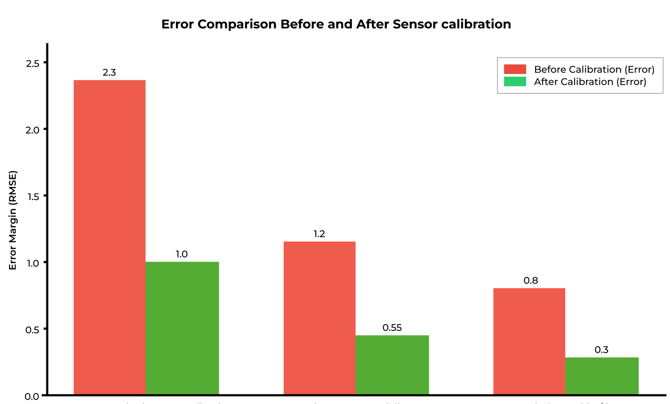

Figure 11 Comparison of RMSE values before and after sensor calibration for atmospheric pressure, air temperature, and wind speed.

CONCLUSION

The verification of the off-grid operation capacity of the system is another important expected result. Thanks to the solar panel and battery management system, the station is aimed to be able to collect data continuously for at least 48 hours even on cloudy days. By using the deep-sleep modes of the ESP32 effectively in software, it is expected that the average power consumption of the system will be minimized, thus ensuring energy continuity. Additionally, the outer case to be designed to protect the hardware against environmental factors (rain, dust, humidity) is expected to ensure the longevity of the system.

The developed prototype is expected to be produced at a much lower cost (approximately 1/5 ratio) compared to industrial weather stations with similar features. In conclusion, this developed system is aimed to contribute to the literature in the field of domestic data collection systems and to create a scalable infrastructure for future "smart agriculture" or "smart solar farm" projects. In future studies, it is planned to further develop the modular structure by powering the system with solar energy and integrating long-range communication protocols such as LoRaWAN.

Ethical standard

The authors have no relevant financial or non-financial interests to disclose.

Availability of data and material

Not applicable.

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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