*FUDMA Journal of Sciences (FJS)*
*ISSN online: 2616-1370*
*ISSN print: 2645 - 2944*
*Vol. 9 No. 8, August, 2025, pp 188 – 197*
*DOI: https://doi.org/10.33003/fjs-2025-0908-3790*

# DESIGN AND IMPLEMENTATION OF AN ENERGY-EFFICIENT SMART WEATHER STATION USING IOT AND SENSOR TECHNOLOGY

***[1]Balami B. Yusuf, [2]Danladi Ali and [2]Dale W. Medugu**

[1]Department of Science Laboratory Technology, School of Science Technology, Federal Polytechnic, Mubi.
[2]Department of Pure and Applied Physics, Adamawa state University, Mubi.

*Corresponding authors' email: bwanthlala20@yahoo.com

## ABSTRACT

The increasing demand for accurate and real-time weather data necessitates the development of innovative monitoring systems that emphasize energy efficiency and sustainability. This paper presents the modeling and development of a smart weather station using sensor technology, integrating a comprehensive array of meteorological sensors, a low-power microcontroller, and renewable energy sources. The process involved the design and simulation of the station using Proteus software, hardware implementation, prototype validation, and determination of power consumption. By employing low-power components, the system reduces energy usage while maintaining uninterrupted operation. The performance of the developed station was evaluated against the Davis Vantage Pro2 weather station, serving as the reference. Statistical analysis showed a strong correlation between both stations, with $R^2$ values exceeding 0.9, and relatively low root mean square error (RMSE), mean bias error (MBE), and mean absolute error (MAE), indicating reliable data accuracy. Power consumption tests revealed a consistent current draw of approximately 0.1663 A (0.84 W), significantly lower than typical full-featured commercial systems. This highlights its suitability for off-grid or remote environments where energy conservation is critical. This energy-efficient smart weather station contributes to more localized, responsive weather monitoring, particularly beneficial for agricultural planning, environmental studies, and climate research. Its integration of sustainable design and reliable performance demonstrates a practical approach to addressing meteorological monitoring challenges while advancing green technologies in environmental data acquisition.

**Keywords**: Smart Weather Station, Energy Efficient Weather Monitoring, Meteorological Sensors, Cloud Platform Weather Data, Real-Time Weather Data

## INTRODUCTION

Smart weather stations are IoT-based systems that are designed to monitor and forecast environmental conditions. These stations typically incorporate various sensors to measure parameters such as temperature, humidity, pressure, rainfall, wind speed, and soil moisture (Üçgün & Kaplan, 2017; Patil *et al*., 2014; Bella *et al*., 2023; Haefke *et al*., 2011). The data collected by these sensors are processed by microcontrollers and transmitted wirelessly to central stations for storage and analysis (Patil *et al*., 2014; Haefke *et al*., 2011). Smart weather stations offer advantages over traditional systems, including real-time monitoring, remote access, and the ability to easily add additional sensors or stations (Bella *et al*., 2023; Haefke *et al*., 2011). These systems have applications in various fields, including agriculture, climate research, and disaster management (Bella *et al*., 2023). Compared to professional meteorological systems, smart weather stations are more cost-effective and accessible for individual use (Üçgün & Kaplan, 2017), making them valuable tools for local weather monitoring and forecasting.

The design and implementation of an energy-efficient smart weather station for renewable energy applications and air quality assessment at Adamawa State University and its environs is a timely and necessary initiative. The region, like many parts of northeastern Nigeria, faces challenges related to unreliable power supply and limited access to continuous, high-quality environmental data. Accurate and real-time weather information is crucial for optimizing renewable energy systems—such as solar photovoltaic installations, which have shown strong potential in the area due to high solar radiation levels—and for monitoring air quality to protect public health and the environment (Mshelia, 2021; Balami, *et al.,* 2024).

Recent studies have highlighted the viability of solar energy projects in nearby locations like Mubi, where a 1 MW grid-connected solar photovoltaic power plant was assessed to be both economically sustainable and environmentally beneficial, reducing greenhouse gas emissions significantly (Luqman, *et al.*, 2023). Leveraging such renewable energy potential requires precise meteorological data to maximize energy generation efficiency and system reliability (Bai, *et al.,* 2024).

Furthermore, the integration of energy-efficient microcontrollers and sensor modules powered by renewable energy sources such as solar panels ensure autonomous operation even in off-grid or power-inconsistent environments common in Adamawa State (Vasira, *et al.*, 2024; Sarmeje, *et al.,* 2023). Wireless communication technologies enable remote data access and real-time analysis, facilitating timely decision-making for energy management and air quality control.

This approach not only supports the sustainable deployment of renewable energy systems on campus and in the surrounding communities but also contributes to environmental monitoring and disaster preparedness. The development of such a smart weather station aligns with regional efforts to promote clean energy, reduce carbon footprints, and enhance resilience against climate variability (Adamawa State Government, 2024). It also fosters technological innovation and capacity building within Adamawa State University, positioning it as a hub for sustainable environmental solutions in the region. Unlike prior works, this study integrates $CO_2$ and $NO_2$ monitoring with low-power IoT.

Despite the increasing deployment of weather monitoring systems, a significant gap remains in the development of smart weather stations that combine real-time data acquisition with energy-efficient operation, particularly for remote or off-grid environments. Many existing systems rely on power-intensive components or grid-dependent setups, which limit their sustainability and long-term deployment in energy-constrained regions (Ter, *et al*., 2025). Addressing this gap, the present study aims to design and implement a low-power, smart weather station using modern sensor technology and renewable energy integration.

The primary objective of this research is to design a smart weather station that autonomously measures key meteorological parameters using embedded sensors. Specifically, the research seeks to: Design a smart weather system capable of automatic environmental monitoring using sensor arrays; Simulate the designed system using Proteus software to verify its functionality prior to hardware development; Implement the hardware prototype of the weather station using low-power components and microcontrollers; Validate the station's performance by comparing its readings with data from the Davis Vantage Pro2 automatic weather station, and Determine the overall power consumption of the developed system to assess its suitability for energy-efficient, long-term deployment.

By directly responding to the literature gap in sustainable and energy-efficient weather monitoring solutions, this study not only advances the field of environmental instrumentation but also supports practical applications in precision agriculture, climate monitoring, and remote sensing.

## MATERIALS AND METHODS

### Materials

The components utilized for developing the smart weather station include: Microcontroller: ATmega 328P-PU, Sensors: DHT22 (temperature and humidity), BMP180 (atmospheric pressure), OPT3001 (light intensity), MQ135 ($CO_2$ and $NH_2$ concentration), Wind Measurement: Anemometer and wind vane, Communication: ESP8266 Wi-Fi module, Display: Green 2004 LCD, Power System: Solar panel, charge controller, LM7905 voltage regulator, and 12V deep-cycle rechargeable battery, Additional Components: Soldering iron, digital multimeter, toggle switch, breadboard, vero board, soldering lead, white plastic casing, IN4007 diode, 18V DC step-down to 5V regulator, serial terminal, and connecting wires.

### System Design

The weather monitoring device is composed of several key units: a power supply unit, a microcontroller, and a sensor module responsible for detecting atmospheric parameters such as temperature, humidity, pressure, light intensity, wind speed, wind direction, carbon dioxide ($CO_2$), and nitrogen dioxide ($NO_2$). Additional units include the data transmission module and the display interface. The design and functionality of each section are described in the subsequent subsections.

### Power Supply Unit

The power supply unit delivers the necessary electrical energy to operate the weather station for continuous environmental monitoring. In this design, the station is powered using solar energy, leveraging the abundant sunlight available in tropical regions.

The unit comprises a solar panel, charge controller, rechargeable battery, and voltage regulation circuitry. Before detailing the design of this section, determining the device's overall power requirement is essential, as it influences the sizing of each sub-unit. The total power demand is calculated by summing the individual power ratings of the primary components used in the system.

The weather station operates at a nominal voltage of 5V. The power rating (P) is determined using the relation:

$$P = IV \text{ or } P = \frac{V^2}{R} \quad (1)$$

The total load of the solar-powered, microcontroller-based weather station is obtained by aggregating the power consumption of all individual components.

#### *Choice of Solar panel*

The selection of solar panels, including their quantity and electrical specifications, relies on a series of calculations and estimations. The deployment location of the device is essential. Nigeria typically experiences wet and dry seasons; therefore, average radiation will be considered in this analysis. The required daily energy demand $E_{rd}$ is 217.68 Wh/day and the average solar radiation data in a day (that is the sun hour, $T_{sh}$) is 9 hours (Okonkwo and Nwokoye, 2014). To compute the average peak power ($P_{ave,peak}$) that can be extracted using a solar panel, we make use of the equation:

$$P_{ave,peak} = \frac{E_{rd}}{T_{sh}} \quad (2)$$

Total DC current $I_{dc}$ is calculated by using the equation:

$$I_{dc} = \frac{P_{ave\ peak}}{V_{dc}} \quad (3)$$

Next, the number of modules in series ($N_{sm}$) is calculated by dividing the system dc voltage (battery voltage) by the rated maximum voltage of each module $V_{pm}$ (the module to be utilized is rated 18V).

Using the equation $N_{sm} = \frac{V_{dc}}{V_{pm}}$, (4)

Next, we obtain the number of module in parallel ($N_{pm}$) by dividing the total dc current of the system by the rated current of one module $I_{rm}$, (maximum current of module used) as in the equation:

$$N_{pm} = \frac{I_{dc}}{I_{rm}}, \quad (5)$$

#### *Charge Controller*

The charge controller's specification is contingent upon the rating calculation of its current and voltage. The charge controller current is determined by the equation:

$$Irec = Isc \times Npm \times Fsafe \quad (6)$$

Where, $I_{sc}$ is the short circuit current of the panel

$N_{pm}$ is the number of parallel module

$T_{safe}$ is the safety factor of the charge controller

Number of charge controller $N_{cc}$ was calculated using the equation,

$$N_{cc} = \frac{I_{rcc}}{I_{cc}}, \quad (7)$$

where $I_{cc}$ = charge controller current

#### *Battery*

The battery functions as the system's power source. The battery is the repository for the electrical energy produced by the solar module. The DC voltage supply for the device will be a 12V rechargeable deep cycle battery. Below are some of the battery characteristics that need to be calculated:

The energy required to operate the Smart Weather Station ($E_s$), and the number of hours in a day (hr) are the components of the daily average energy demand in Watt-hour ($E_d$).

$$E_d = E_s \times hr(W/day) \quad (8)$$

To ascertain the estimated energy storage ($E_{est}$) of the battery, we make use of the equation

$$E_{est} = E_d \times D_{aut} \quad (9)$$

Where, $D_{aut}$ is the number of autonomy days of one day.

Safe energy store is given as:

$$E_{safe} = \frac{E_{est}}{D_{dis}} \quad (10)$$

Where $D_{dis}$ is the maximum depth of discharge of the battery chosen to be 75%.

The total capacity of a battery bank is obtained by using:

$$C_{tb} = \frac{E_{safe}}{V_b} \quad (11)$$

***Voltage regulation***

Voltage regulation is very vital for the device to peg the 12V battery output to a level tolerable to the constituent components of the weather station. A maximum voltage of 5V is sufficient and as such a LM7905 voltage regulator was utilized.

**Microcontroller Unit**

The electronic control component comprises an Arduino ATmega 2560 microcontroller. It functions as the core of the device. All other components are interfaced with the microcontroller which controls and synchronizes the entire operations of the modules and handles data and command from external devices.

**Sensors**

The sensor part of the smart weather station consists of the following:

***Temperature and relative humidity monitoring unit***

The DHT22 sensor was utilized to simultaneously detect and record air temperature and relative humidity. DHT22 was chosen for its higher accuracy and wider temperature/humidity range than DHT11. However, it has slower response time and is more expensive.

***Pressure monitoring unit***

This portion use the BMP 180 sensor to measure ambient pressure and provide it as an analog output to the microcontroller. BMP180 was selected for its compact size, low power use, and accurate pressure readings. However, it lacks humidity sensing and has lower precision than newer models like BMP280.

***Gas unit***

The MQ-135 gas sensor is capable of detecting gases such as ammonia ($NH_3$), sulfur (S), benzene ($C_6H_6$), carbon dioxide ($CO_2$), $NH_2$, and various other hazardous gases and vapors. MQ-135 was chosen for its ability to detect multiple air pollutants cost-effectively. However, it lacks selectivity, requires calibration, and is affected by temperature and humidity variations.

***Wind speed and direction monitoring unit***

A three-cup anemometer was utilized to measure wind speed while a wind vane was used to measure wind direction. The three-cup anemometer and wind vane offer reliable, low-cost wind speed and direction measurement. However, they have moving parts prone to wear and are less accurate in turbulent airflow.

***Light Intensity unit***

The sensor BH1750 (ROHM Semiconductor) is utilized for measuring illumination, interfacing with the microcontroller through a software-implemented I2C bus. BH1750 was selected for its digital output, high sensitivity to light, and low power consumption. However, it may struggle under high-intensity light and lacks directional light sensing.

**Display Section**

This part employs the Green 2004 LCD panel, featuring a resolution of 84 by 48 pixels, to present real-time weather information for on-site users. The Green 2004 LCD was chosen for its clear, multi-line display and low power use. However, it lacks color, graphical capabilities, and visibility under low-light conditions.

**Data Transmission Unit**

A Wi-Fi module functions as the data transmission conduit utilizing Universal Asynchronous Receiver Transmitter (UART). The Wi-Fi module transmits a signal to the microcontroller during the initialization process, prompting the microcontroller to relay processed atmospheric data to the Wi-Fi module for upload to an online server. Real-time weather information can be accessible via the internet server for remote users.

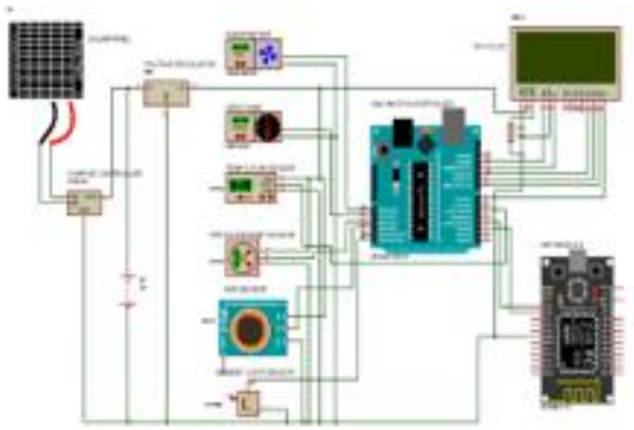


Figure 1: A complete circuit diagram of the smart weather station

**Simulation Method**

The simulation of the device was carry-out using Proteus v8.7 software (Alnaham, & Suliman, 2015). An Arduino IDE was used to expedite the development process of the proposed system.

**Implementation of the experimental design**

This pertains to the physical building and implementation of the weather station as per the specified design.

***Electronic based construction***
All components were sourced from electronic markets in Nigeria and assembled on a breadboard to verify their functionality before being hard-wired onto a Vero-board by soldering.

***Mechanical construction***
A metal stand was meticulously fabricated from steel pipes and angle iron to support the instrument. Provisions were developed to properly support the solar panel and the engineered gadget.

***Software implementation***
The weather station is microcontroller-oJperated and web-based. Consequently, it is contingent upon the software. The software designated for this project is Proteus version 8.7, a program utilizing C++ machine language.

***Website implementation, The ThingSpeak Technology***
In this work, logged atmospheric data are hosted on the web using Internet of Things (IoT). A platform of IoT, Thingspeak was employed as an interface between the device and out-of-site users. Thingspeak was used to manage network connection, real time data collection from sensors, storage of data collected and analysis or visualization of collected data.

**Calibration and Validation of the smart weather station**
***Reference Weather Station***
The evaluation of the prototype smart weather station's performance will involve a comparison with measurements obtained from a meteorological station that acts as a backup for the official ADSU Mubi main campus site, i.e., The Davis Vantage 2.

***Experimental Setup***
The prototype smart weather station was installed adjacent to the Davis Vantage Pro2 automatic weather station for performance comparison. It was oriented toward the north and calibrated against the reference station to ensure accurate wind direction and solar intensity measurements. Data for all parameters were logged at 30-minute intervals, either as cumulative or instantaneous values, depending on the variable. The observation period lasted 12 hours, and all measurements were taken at the Faculty of Science, Adamawa State University, Mubi.

***Performance Analysis***
To evaluate and compare the performance of the two stations, several statistical indicators will be applied. The Arithmetic Mean (μ) of the observed parameters will first be computed. The Coefficient of Determination ($R^2$) (Equation 12) will be employed to assess the level of agreement between the stations. The Root Mean Square Error (RMSE) (Equation 13) will serve as an indicator of deviation, giving greater weight to larger discrepancies and, therefore, showing higher sensitivity to outliers (Walther & Moore, 2005).
Additionally, the Mean Bias Error (MBE) (Equation 14) will be calculated to determine the average bias between the measured values and the reference station, where positive values represent overestimation and negative values indicate underestimation. However, since MBE is prone to error cancellation when positive and negative deviations offset each other, it will be analyzed alongside other metrics (Ruiz & Bandera, 2017). Finally, the Mean Absolute Error (MAE) (Equation 15) will be considered as it measures the absolute difference between measurements and the reference without being affected by error cancellation and is less influenced by outliers compared to RMSE (Walther & Moore, 2005).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(y_i-\hat{y}_i)^2}{\sum_{i=1}^{N}(\hat{y}_i-\bar{y})^2} \quad (12)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2} \quad (13)$$

$$MBE = \frac{\sum_{i=1}^{N}(y_i-\hat{y}_i)}{N} \quad (14)$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|y_i - \hat{y}_i| \quad (15)$$

where y is the reference value, $\hat{y}$ is the measured value, $\bar{y}$ is the mean of the reference value, and N is the number of measurements.

**Power consumption of the weather station**
A digital Ammeter was used for this purpose. The current consumption of the weather station was measured using an ammeter which is connected in series with the power supply source and the reading on the ammeter was observe directly. This value indicates the current consumption of the weather station, typically measured in milli-amperes (mA) or amperes (A). By multiply the power consumption of the weather station by the number of hours the weather station operates daily we get daily energy consumption (in watt-hours).

**RESULTS AND DISCUSSION**
**Design Analysis**
***Power Unit***
The total power rating of all the components/devices used was found to be 0.84 watts.

**Solar panel**
PV array sizing obtained were: Required daily energy demand ($E_{rd}$) is equal to 217.68Wh/day. Average peak power, $P_{ave.peak}$ is equal to 24.19W. Total DC ($I_{dc}$) is equal to 4.84A. Number of series modules ($N_{sm}$) is equal to 0.67~ 1 and, Number of parallel modules ($N_{pm}$) is equal to 0.67~1.
The requirement for both connections necessitates many modules. Consequently, none of them can be executed. Consequently, a singular module must capture the sun's radiant energy. A mono-crystalline solar module, specifically the BL5P-12(SW-5W-P), was selected to serve as the voltage source for the weather station, facilitating continuous atmospheric data collecting.

**Charge controller**
The required charge controller current ($I_{rcc}$) is 0.375A and the number of charges controller ($N_{cc}$) is 0.75 (~1). But 0.375A charge controller is not commercially available. Therefore, a 0.5A-rated charge controller will be utilized. Thus, the specification will be $V_{dc} = 5V$, $I_{cc} = 0.5A$.

**Battery**
The Daily average energy $E_d$ was 20.16 Wh/day and the estimated energy stored ($E_{est}$) was 20.16 Wh. The Safe energy stored $E_{safe}$ was 26.88W. The total capacity of the battery is the battery bank ($C_{tb}$) and was found to be 2.24A.

**Simulation Results**

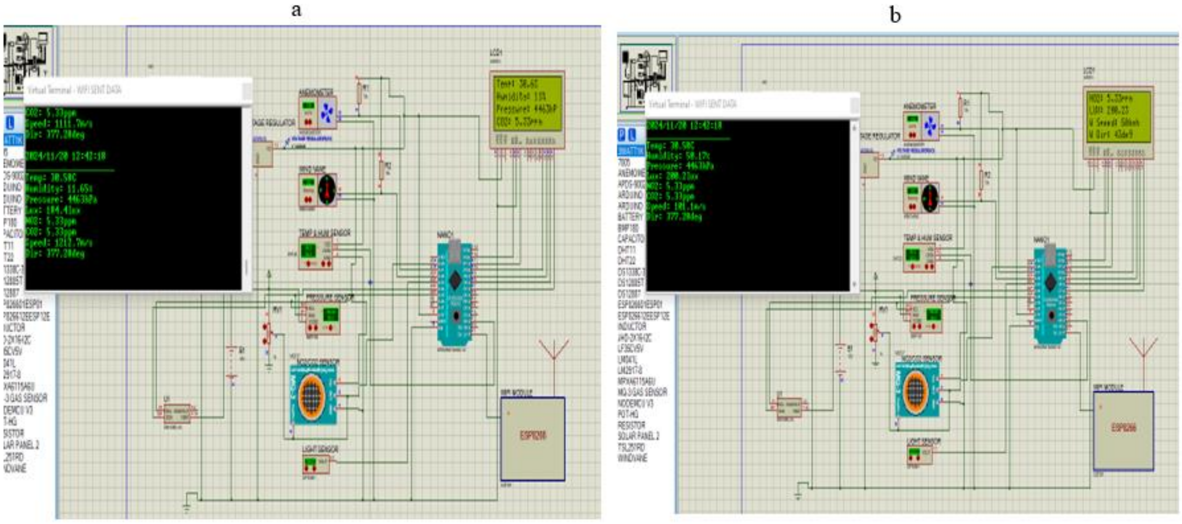



Figure 2: Simulation results

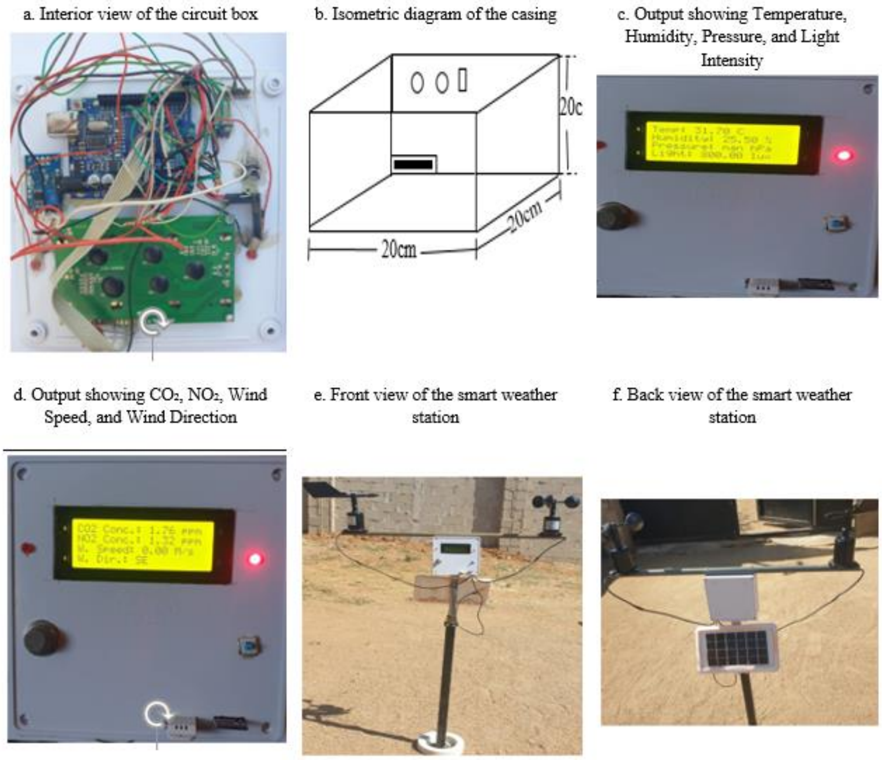
Figure 2a shows the simulation results after varying temperature to 20.6$^0$C, Humidity to 11%, Pressure to 4463hp, and $CO_2$ to 5.33 ppm. Figure 2b shows the simulation results with $NO_2$ 5.33 Lux equal to 200.23, Wind speed to 50kmh, and Wind direction to 43$^0$.

The outcome of the simulation is seamless. A favorable simulation outcome serves as a technical performance assessment and suggests that the gadget will function efficiently during actual operation.

**Design Implementation**

***Circuit Implementation and Casing***

The construction was carried out first on a breadboard to ensure that the circuit was working as required, then transferred to the Vero board for permanent soldering. The interior view of the circuit box with permanent soldering on the Vero board is shown in Figure 3a. The casing used was a white-coloured plastic material for mechanical protection. It is provided with 2no. holes for the light intensity and gas concentration, 2no. of windows for the temperature/ humidity, and a USB port. 4no. of hole groove edges of its top side for screw lock, 1no. hole for the power switch tighten by nut and 1no. of hole for LCD. Figures 3b shows the isometric diagram of the casing, Figures 3c-d shown the measured parameters while, the complete packaged device in a casing are shown in Figures 3e- f.




Figures 3: Design and Implementation Details of the Smart Weather Station


Figure 4: The ThingSpeak results for weather parameters

**Validation Test Results**

The results for each studied weather variable are presented below.

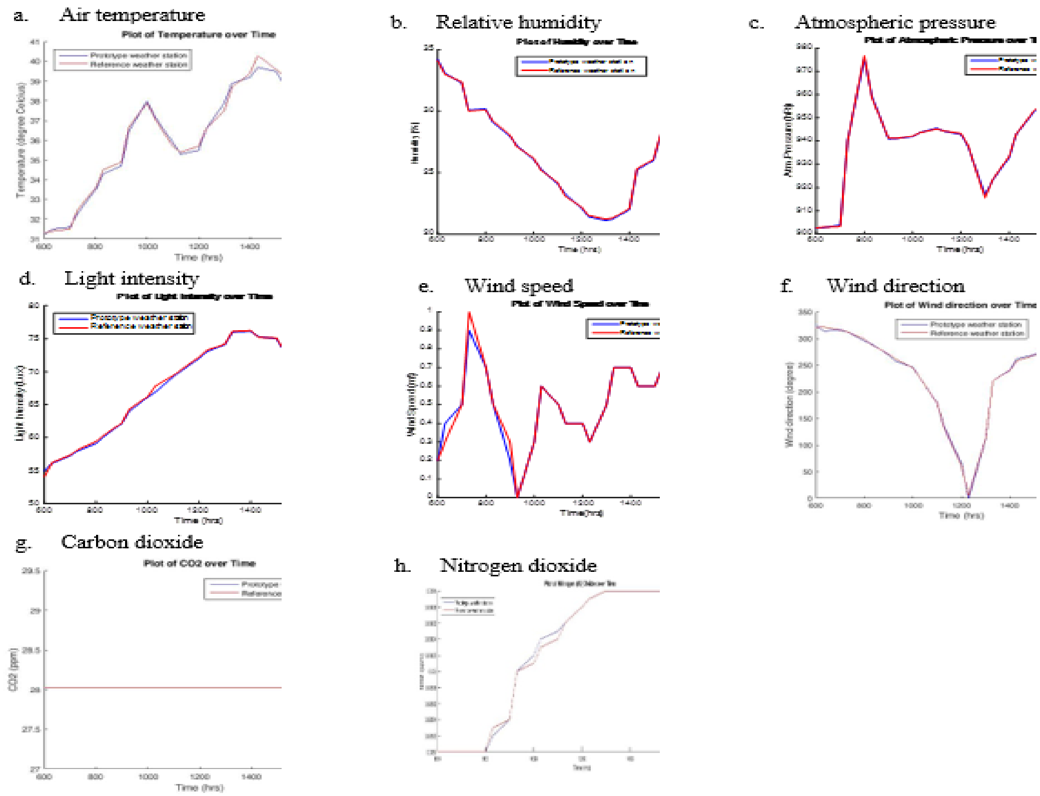



Figure 5: Time-varying weather parameters

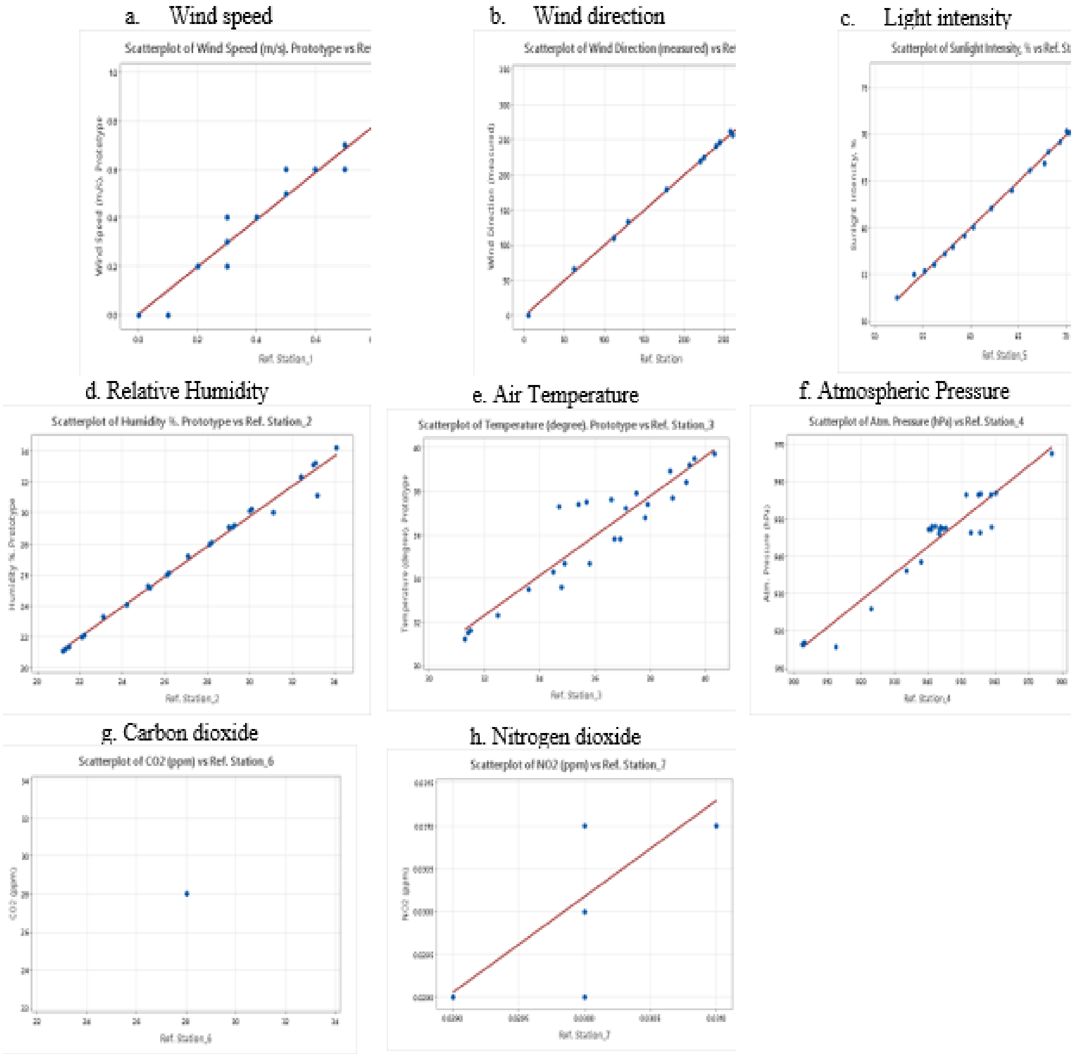



Figure 6: Scatter Plot of the smart weather station variables verses the reference weather station variables

**Table 1: Statistical Summary of the Performance of the Smart Weather Stations Compared to the Davis Vantage Pro2 Weather Reference Station**

| Variable | $R^2$ | RMSE | MBE | MAE |
|---|---|---|---|---|
| Light Intensity | 0.9984 | 0.3040 | 0.0920 | 0.2200 |
| Temperature ($^0$C) | 0.9930 | 0.2145 | 0.0760 | 0.1720 |
| Atm. Pressure (hPa) | 0.9990 | 0.1161 | 0.0200 | 0.4360 |
| Relative Humidity (%) | 0.9851 | 0.4850 | 0.1440 | 0.2240 |
| Wind speed (m/s) | 0.9642 | 0.0447 | 0.0040 | 0.0200 |
| Wind direction ($^0$) | 0.9988 | 2.8213 | 0.0400 | 2.1200 |

**Power Consumption**

The smart weather station was found to have a constant current consumption of approximately 0.1663 A (0.84W), although the station takes measurements in periods of 30 minutes, due to the lack of optimization never enters into a low power mode, consequently the peripherals always maintain a constant power draw.
The Daily Energy Used by the station per day =
19.95 Wh/day and the Monthly Energy Used was ≈
598.56 Wh or 0.59856 kWh while the Yearly energy used ≈
7.28 kWh.

**Discussion**

The results presented in the previous sections show that sensor technology can be used to measure weather variables. The smart weather station is designed to be energy-efficient, using low-power sensors and communication modules to minimize power consumption. This allows the station to operate for extended periods on a battery or solar energy source. 0.84W is needed to run the smart weather station which is capable of measuring eight weather variables including wind speed and direction. The power needed to run a weather station typically ranges from about 0.3 to 70W, depending on the number of sensors and the type of data being collected. Basic stations with fewer sensors and less data

processing consume around 0.3W, while more advanced or connected stations may require up to 70W or more (Faid, *et al*, 2021; Iram, et al., 2023).
After obtaining the results, verifying the correct functioning of the weather station, and comparing them with the Davis vantage Pro2 automatic weather station source, each of the obtained graphics can be analyzed.
To better visualize the comparison of the two stations, the full-time series is given in Figures 10.
Table 1 summarizes the statistical performance analysis of the Smart weather stations compared to the reference station. Overall, $R^2 > 0.9$ and relatively low RMSE, MBE, and MAE were found for most variables except wind direction. The higher RMSE (2.82°) in wind direction suggests misalignment or mechanical drift, indicating the need for regular calibration to ensure accurate orientation and compensate for environmental and sensor-induced deviations (WMO, 2018).
In the following, each variable is assessed in more detail.

***Light Intensity***
Figure 5d shows 12 hours of data collection per day, 30-minute interval measurement of sunlight by the smart weather stations. The timing and variability of the sunlight intensity during the day are well captured by the Smart weather station. However, the maximum measured sunlight intensity is slightly lower than that of the reference station.
The scatterplots of the smart weather station vs. the Davis Pro2 weather station (Figure 6c) confirm the overall good agreement of the stations, with an $R^2$ of 0.9984 (Table 1). The plots show little scatter and RMSE is 0.3040 lux (Table 1). Light intensity values >60 Lux show a small underestimation by the Smart weather station (Figure 5f).
The presented results for the Smart weather station generally agree well with the analysis by Anand and Molnar, (2018), which compared the 2017 version of the ATMOS41 station with a SwissMetNet station. In their study, a lower bias of 8.9% was found compared to the one in this comparison (9.2%). This may be attributed to the overall lower radiation during the winter period studied by Anand and Molnar, (2018) as opposed to the early summer period of this study which included many sunny days. Despite the 2 km distance between the two stations, the authors observed a lower MAE (13.57W/m$^2$) than what was found in this study, which may again be related to the characteristics of the observation period.
Despite the small systematic deviation from the reference station, the quality of the light intensity measurements provided by the Smart weather station was satisfactory.

***Air Temperature***
Figure 5a present time-varying air temperature of the smart weather station for 12 hours. Temperature dynamics are well captured by the smart weather stations. The scatterplots (Figure 6e) and statistical analysis (Table 1) show excellent performance of the smart weather station with values close to the identity line, little scatter, and $R^2$ close to 1. RMSE and MAE are 0.2145 and 0.1720 respectively, nearly the same RMSE and MAE reported by Anand and Molnar, (2018).

***Atmospheric Pressure***
Figure 5c Present time-varying atmospheric pressure measured by the smart weather station. The smart weather stations closely follow the reference station with small differences consistently found during noon and evening period. The high $R^2 = 0.9990$ indicates good agreement with the measurements. However, RMSE is small with a relatively large MAE of 0.1161 and 0.4360 hPa, respectively. In agreement with Anand and Molnar, (2018), the scatterplots (Figure 6f) show a small bias towards higher values measured by the smart weather station compared to the reference station (MBE between -2.276 and 1.01 hPa). While the smart weather station performs satisfactorily within the accuracy of ±1 hPa, the pressure sensor does not meet the "achievable uncertainty" requirement of 0.3 hPa as commissioned by the WMO (2008). Therefore, the smart weather station shows only moderate performance in measuring atmospheric pressure compared to the reference station.

***Relative Humidity***
Figure 5b shows relative humidity as measured by the smart weather stations throughout the day of the measured time series. Relative humidity is captured well by the smart weather station, with slightly higher humidity measured at 6 am. This matches the observed small underestimation of temperature during that time, as discussed in earlier. Smart weather station additionally shows low values during the daytime minimum humidity. The statistical summary (Table 1) shows $R^2 \geq 0.9851$ and RMSE and MAE are 0.4850 to 22.4%, respectively.
The scatterplot for the smart weather station (Figure 6d) confirms a small bias towards higher values for lower relative humidity and towards lower values when humidity is high. As a result, the smart weather station shows a relatively higher MBE of 14.4% compared to the Atmos2 (MBE of 0.25) study by Dombrowski, et al., (2021).
The smart weather stations tend to saturate at 100% relative humidity more frequently than the reference station, which seems to verify the observation of Anand and Molnar, (2018) and which may also be related to the underestimation of air temperature, as discussed earlier.

***Wind Speed and Direction***
Figure 5e presents time-varying wind speed measured by the smart weather station throughout the day. The wind dynamics measured by the smart weather station match well with the measurements of the Davis Volta Pro2 weather station. However, measurements by the smart weather station show lower peak values and a larger variability compared to the Davis Volta Pro2 weather station, which can be explained by the finer resolution of the anemometer of the Davis Volta Pro2 weather station.
The scatterplots (Figure 6a) show a relatively large scatter around the identity line, with an $R^2 = 0.9642$. The widespread in wind measurements is likely a result of small-scale turbulence caused by surrounding instruments, and which are captured due to the rapid response of ultrasonic anemometers to sudden changes in wind speed (Ammann, 1994). The scatter can be reduced when small-scale differences average out over larger periods. RMSE and MAE are 0.0447 and 0.0200, respectively (Table 1).
Wind direction in degrees Celsius was also compared with that of the reference station. The measurements from the smart weather station agree well with the observed wind direction of the reference station. Strong winds were mainly observed from the West and South-West and sometimes from the North, while East winds were considerably weaker. Wind direction from the smart weather stations agree with the main wind directions and speed with the reference station. Although our results do not show a significant improvement in the measurement, wind direction is still measured reasonably well by the smart weather station.

***$NO_2$ and $CO_2$ Level***

The values of the concentration of $NO_2$ level in the atmosphere indicate a small increase in determined time frames (Figure 5h). This increase is caused by the agglomeration of cars during the hours of entry and exit of students from the campus according to the educational schedule.

For $CO_2$, there is a constant concentration of 0.03 ppm throughout the day in the atmosphere (Figure 5g).

The prototype datasets fit the reference datasets smoothly, which means that we could examine the behavior of the meteorological variables quickly and at a low cost.

***Power Consumption***

Smart, IoT-based weather stations are designed for low power use. In our case the station draws about 0.832 W under normal operation – far less than most full-featured systems. By contrast, typical home and hobbyist Wi-Fi weather consoles draw on the order of 0.3–0.5 W continuously. For example, the Ambient WS-2902 consumer Wi-Fi weather station reports a power consumption of about *0.5 W* (rising to ~1.25 W only during Wi-Fi setup) (Ambient Weather, n.d.). Similarly, small data loggers and sensor hubs (e.g. Davis's WeatherLink Live gateway) have standby draws under 0.1 W **(**Davis Instruments, 2022**)**. At the extreme low end, specialized IoT prototypes have demonstrated *milliwatt-scale* operation: one optimized wind-monitoring node consumed only ~$0.9\times10^{-3}$ W in deep sleep (Leelavinodhan, et al., 2021), and averaged roughly 0.1 W (29.5 mA at 12 V) during activity (Kazman, et al., 2018).

By contrast**,** professional research-grade weather stations typically use much more power. Integrated sensor suites (e.g. Campbell Scientific's ClimaVUE or Young rain gauges) have quiescent currents of only a few milliamps, but when active their full systems (datalogger + sensors + communications) draw several watts. For example, a Campbell CR1000 datalogger has idle current <1 mA at 12 V, ~0.01 W) and active currents of ~10–28 mA (0.12–0.34 W) (Campbell Scientific, n.d.). However, high-end AWS deployments often include power-hungry components. Heated precipitation gauges are notorious consumers: e.g. Campbell's CS700H heated rain/snow gauge draws 5.8 A at 12 V (≈70 W) when its heater is on (Campbell Scientific 1, n.d.). In practice, large AWS installations use tens to hundreds of watts (or AC mains) to power heated sensors, high-frequency radios, and datalogging, requiring sizable solar panels or AC backup. Even so, non-heated professional sensors can be quite frugal: The ClimaVUE-50 all-in-one weather sensor runs on about *0.4–1.0 mA at 12 V* (only ~0.005–0.012 W average) when sampled every minute (Campbell Scientific 2, n.d.).

The key point is that 0.832 W is very low by weather-station standards. It is well below typical consumer consoles and orders of magnitude below anything with heated sensors. This low draw means the station can be powered by a small solar panel or modest battery. For instance, a 5–10 W solar panel (common even for small IoT nodes) easily supplies tens of watt-hours per day, which more than covers a 0.8 W load. In fact, research has shown ultra-low-power AWS designs operating on tiny batteries: one study reported only *0.0998 Wh* energy per hour of operation (≈ 0.1 W average) for a field IoT node (Kazman, et al., 2018). In sleep mode its circuitry used virtually zero power (Leelavinodhan, et al., 2021). These citations illustrate that 0.832 W is indeed on the very low end of the spectrum, enabling solar- or battery-powered remote monitoring with minimal hardware.

Because of its low power draw, a 0.832 W weather station is ideal for remote and off-grid use. It can run for long periods on small solar panels or battery packs without maintenance. For example, many IoT monitoring networks deploy such sensors in agriculture, ecology, and infrastructure monitoring precisely because they can operate on solar harvesters and last seasons on a battery. Even in regions without mains power, the station can be paired with a ~5–10 W panel and a small lead-acid or Li-ion battery and run autonomously. This makes it well suited to applications like precision farming, wildfire/weather buoys, or mobile field units, where power is at a premium. In short, the sub-watt requirement of the smart station means no heavy power infrastructure is needed – a far cry from the multi-amp, multi-panel setups of traditional meteorological installations.

However, the design lacks a low-power sleep mode, causing continuous energy draw even during idle periods. This limits battery life and overall efficiency, especially in off-grid settings where energy conservation is critical. Future iterations could optimize power by adding sleep cycles.

## CONCLUSION

The modeling and implementation of a smart weather station have been shown which besides provide measurements of atmospheric variables, offers wireless communication, energy autonomy, and it is an energy efficient station which work for an extended period of time compared to the existing station. It enables excellent quality predictions over a user-defined prediction horizon. As such, we anticipate that a commercial version of such a device will have a large range of practical applications, examples being in PV plants, energy-building management systems, and agricultural applications. Future work could integrate machine learning for predictive analytics.

## REFERENCES

Adamawa State Government. (2024). *Adamawa State climate change policy draft*. https://eerce.org/wp-content/uploads/2024/06/ADAMAWA-STATE-CLIMATE-CHANGE-POLICY-DRAFT.pdf

Alnaham, M. Y. M., & Suliman, M. M. A. (2015). Microcontroller based system for voltage monitoring, protection and recovery using Proteus VSM software. *International Journal of Computer Applications, 118*(3), 1–5. https://doi.org/10.5120/20722-3069

Ambient Weather. (n.d.). *WS-2902 smart WiFi weather station with WiFi remote monitoring & alerts*. Ambient Weather. Retrieved May 13, 2025, from https://ambientweather.com

Ammann, S. K. (1994). *Ultrasonic anemometer* (U.S. Patent No. 5,343,744). U.S. Patent and Trademark Office. Retrieved from https://patents.google.com/patent/US5343744A

Anand, M., & Molnar, P. (2018). *Performance of TAHMO Zurich Weather Station* [Technical report]. Institute of Environmental Engineering, D-Baug, ETH Zurich, Switzerland. Retrieved from https://ethz.ch/content/dam/ethz/special-interest/dual/sas4sd-dam/documents/ETHZurich_TAHMOStation_DataReport.pdf

Bai, Y., Li, Y., & Zhang, X. (2024). *A study on energy efficiency in building management systems: Challenges and solutions*. Energy Reports, 6, 123–134. Retrieved from https://www.sciencedirect.com/science/article/pii/S240584402408900X

Balami, B. Y., Danladi, A., & Medugu, D. W. (2024). Assessment of air pollution level at Adamawa State University Mubi using fuzzy inference system model. *FUW Trends in Science & Technology Journal, 9*(3), 179–184. https://www.ftstjournal.com/uploads/docs/93%20Article%2025%20pp%20179-184.pdf

Bella, H. K. D., Khan, M., Naidu, M. S., Jayanth, D. S., & Khan, Y. (2023). Developing a sustainable IoT-based smart weather station for real time weather monitoring and forecasting. In *E3S Web of Conferences* (Vol. 430, Article 01092). EDP Sciences. https://doi.org/10.1051/e3sconf/20234301092

Campbell Scientific. (n.d.). *CR1000: Measurement and control datalogger*. Retrieved May 13, 2025, from https://www.campbellsci.com/cr1000

Campbell Scientific. (n.d.-a). *CS700H-L: Heated rain gage*. Retrieved May 13, 2025, from https://www.campbellsci.com/cs700h-l

Campbell Scientific. (n.d.-b). *ClimaVue 50: Compact digital weather sensor*. Retrieved May 13, 2025, from https://www.campbellsci.com/climavue50

Davis Instruments. (2022). *WeatherLink 6100 Anleitung* [PDF]. Retrieved May 13, 2025, from https://www.davis-wetterstationen.de/pub/6100_WeatherLink_Anleitung.pdf

Dombrowski, O., Hendricks Franssen, H. J., Brogi, C., & Bogena, H. R. (2021). Performance of the ATMOS41 all-in-one weather station for weather monitoring. *Sensors, 21*(3), Article 741. https://doi.org/10.3390/s21030741 (bonndoc.ulb.uni-bonn.de, pubmed.ncbi.nlm.nih.gov)

Faid, A., Sadik, M., & Sabir, E. (2021). An agile AI and IoT-augmented smart farming: A cost-effective cognitive weather station. *Agriculture, 12*(1), 35. https://doi.org/10.3390/agriculture12010035

Haefke, M., Mukhopadhyay, S. C., & Ewald, H. (2011). A Zigbee based smart sensing platform for monitoring environmental parameters. In *2011 IEEE International Instrumentation and Measurement Technology Conference* (pp. 1–8). https://doi.org/10.1109/I2MTC.2011.5944397

Iram, S., Al-Aqrabi, H., Shakeel, H. M., Farid, H. M. A., Riaz, M., Hill, R., … & Alsboui, T. (2023). An innovative machine learning technique for the prediction of weather based smart home energy consumption. *IEEE Access, 11*, 76300–76320. https://doi.org/10.1109/ACCESS.2023.3271087

Kazman, R., Haziyev, S., Yakuba, A., & Tamburri, D. A. (2018). Managing energy consumption as an architectural quality attribute. *IEEE Software, 35*(5), 102–107. https://doi.org/10.1109/MS.2018.290111643

Leelavinodhan, P. B., Vecchio, M., Antonelli, F., Maestrini, A., & Brunelli, D. (2021). Design and implementation of an energy-efficient weather station for wind data collection. *Sensors, 21*(11), 3831. https://doi.org/10.3390/s21113831

Luqman, R., Kehinde Issa, A.-J., Owolabi, A. B., Yakub, A. O., Same, N. N., Yahaya, A., … Huh, J.-S. (2023). Assessing the viability of a grid-connected PV power plant in Mubi, Adamawa State, Nigeria. *Frontiers in Energy Research, 11*, Article 1205646. https://doi.org/10.3389/fenrg.2023.1205646

Mshelia, R. B. (2021). Assessment of renewable energy potentials of the northeast geopolitical region of Nigeria. *Renewable Energy Sources: Energy Policy and Energy Management,* 2(2), 24–38. https://doi.org/10.17993/2.2021.220244

Okonkwo, G. N., & Nwokoye, A. O. C. (2014). Analysis of solar energy parameters in Bida, Nigeria. *European Scientific Journal, 10*(15), 123–130. https://doi.org/10.19044/esj.2014.v10n15p%C2%A0123

Patil, S. S., Davande, V. M., & Mulani, J. J. (2014). Smart wireless sensor network for monitoring an agricultural environment. *International Journal of Computer Science and Information Technologies, 5*, 3487–3490. Retrieved from https://citeseerx.ist.psu.edu/document?doi=2a40d8f2d0bccecfdfed0981b98b576e23bd3f1e

RAYPCB. (2024, December 9). *Raspberry Pi/WeatherRack — NodeJS weather data station: A comprehensive development guide.* RAYMING. Retrieved from https://www.hackster.io/shaddow1201/raspberry-pi-weatherrack-nodejs-weather-data-station-eea19a

Renke. (n.d.). *Best ultrasonic weather station instrument*. Jiangsu Renke Control Technology Co., Ltd. Retrieved May 13, 2025, from https://www.renkecontrol.com

Ruiz, G., & Bandera, C. (2017). Validation of calibrated energy models: Common errors. *Energies, 10*(10), 1587. https://doi.org/10.3390/en10101587

Sarmeje, C. P., Afolabi, O. A., & Gaya, K. G. (2023). Design and simulation of a microcontroller based weather station. *African Journal of Advances in Science and Technology Research, 12*(1), 18–34. Retrieved from https://publications.afropolitanjournals.com/index.php/ajastr/article/view/600

Ter, K. P., Yakubu, M. S., Momoh, M. O., Abbe, G. E., Agov, T. E., & Alioke, O. C. (2025). Design of an Efficient Power Management System for Solar-Powered UAVS: A Systematic Approach. *FUDMA Journal of Sciences*, *9*(3), 80-87.

Üçgün, H., & Kaplan, Z. K. (2017). Arduino based weather forecasting station. In *2017 International Conference on Computer Science and Engineering (UBMK)* (pp. 972–977). https://doi.org/10.1109/UBMK.2017.8093476

Vasira, P. G., Medugu, D. W., & Sarmeje, C. P. (2024). *Design and implementation of a wireless wind gauge with GUI. Journal of Science Innovation and Technology Research, 5*(3), 179–184. https://africanscholarpub.com/ajsitr/article/view/348

Walther, B. A., & Moore, J. L. (2005). The concepts of bias, precision and accuracy, and their use in testing the performance of species richness estimators, with a literature review of estimator performance. *Ecography, 28*(6), 815–829. https://doi.org/10.1111/j.0906-7590.2005.04080.x

World Meteorological Organization. (2008). *Guide to meteorological instruments and methods of observation* (7th ed.) [WMO No. 8]. Geneva, Switzerland: World Meteorological Organization. https://doi.org/10.25607/OBP-1528