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Development of Weather Monitoring System for Photovoltaic System Performance Prediction and Evaluation

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ABSTRACT

With the rising prominence of solar energy as a renewable power source, there is a critical need for accurate forecasting to enable its efficient integration into power grids. This work addresses the challenge of unpredictable climatic conditions that affect the efficiency of solar energy utilization. We developed an IoT-based weather monitoring system designed specifically for solar prediction, leveraging an integrated sensor suite to accurately measure temperature, humidity, atmospheric pressure, and precipitation. Utilizing Google Sheets for real-time monitoring, the system allows for autonomous data acquisition and offers the unique capability of online data logging, ensuring rapid decision-making capabilities in variable weather conditions. To validate the reliability and accuracy of the system, we compared our recorded data with established PVSyst software models. Results indicate a significant alignment between the real-time data from the proposed system and the PVSyst models, confirming the system's potential in enhancing the predictability and utilization of solar energy. This work sets a foundation for advanced weather monitoring, ensuring the predictive models are representative of real-world conditions, ultimately advancing the solar industry's efficacy and reliability.

Keywords:
Photovoltaic; Weather Wireless Remote Monitoring; Data Visualization, PVSyst

1. Introduction

Solar energy technology is an appealing means of providing renewable energy, addressing global environmental issues, and decreasing reliance on limited fossil fuel supplies [1-5]. However, due to the inherent unpredictability of solar energy availability, which is heavily impacted by meteorological conditions, the integration of solar power into the current grid infrastructure confronts significant challenges. For photovoltaic (PV) systems to be utilized to their full potential and for the grid to remain stable, accurate solar power forecasting is essential [6]. Solar forecasting

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is an important practice in the renewable energy sector since it involves projecting the amount of solar energy that will be produced by a solar power plant or solar panel array at a certain time and location [7]. Accurate forecasting of solar energy production is required for effective management and integration of solar power into the electrical grid [8]. Utilities and grid operators may prepare for and include the inherent variability of solar energy generation with precise solar predictions, guaranteeing a stable and efficient system operation. This study developed a comprehensive weather monitoring system for solar prediction that employs cutting-edge Internet of Things (IoT) technology and industry-standard PVsyst software in order to significantly improve the accuracy of solar power forecasts.

There are two types of solar forecasting models: direct models and indirect models. Direct models are based on physical modelling processes that directly influence solar energy generation, such as the movement of the sun and the exchanges of radiation with the Earth's atmosphere. These models use complicated equations and algorithms to simulate the behaviour of solar radiation and its impact on energy generation. Indirect models, on the other hand, use statistical or Machine Learning (ML) techniques to evaluate previous data and discover patterns that can be used to anticipate future solar energy production [9]. These models do not explicitly account for physical processes, instead relying on past data to create accurate predictions.

Direct models include a variety of methodologies, such as physical models and numerical weather prediction models. To effectively replicate solar energy production, physical models must have a thorough understanding of solar radiation principles and atmospheric physics. Numerical weather prediction models, which are widely used in meteorology, use sophisticated algorithms to simulate meteorological conditions and predict solar irradiation [10]. Indirect models are statistical models and machine learning models that provide precise predictions using previous solar energy-generating data, meteorological data, and other relevant variables. To ensure dependability and precision, these models frequently require substantial training and optimization operations [10].

These models' predictions are used in conjunction with photovoltaic (PV) simulation software to accurately predict solar energy generation. PV simulation software estimates the power output of a PV system using mathematical models based on solar irradiance, temperature, panel properties, and other input variables. These models provide valuable insights into the predicted energy output of a solar power plant or solar panel array under different weather conditions, allowing for effective grid integration and energy management.

Several works have thoroughly assessed and analyzed solar forecasting methods, highlighting their advantages, disadvantages, and specialized applications. These works [11-13] emphasize the importance of solar forecasting for effective solar energy grid integration and address difficulties such as obtaining accurate meteorological data and accounting for complex atmospheric conditions.

In addition to solar forecasts, weather monitoring systems play a crucial role in optimizing the performance of solar PV installations. These systems monitor temperature, humidity, cloud cover, and solar radiation continuously. By collecting real-time data on these parameters, weather monitoring systems allow PV system output to be adjusted to maximize electricity production [14]. They also make it simpler for photovoltaic systems to respond to changing weather conditions, enabling proactive measures to be taken during extreme weather events [15], such as hurricanes or thunderstorms.

Traditional weather forecasting systems usually rely on data from a limited number of ground-based weather stations, which can lead to erroneous and incomplete forecasts. The advent of IoT-based weather monitoring systems in recent years has presented a viable approach to bypassing these constraints. IoT-based systems use a network of sensors to measure a wide range of weather and environmental characteristics, including temperature, humidity, atmospheric pressure, wind speed, precipitation, and air quality. These sensors wirelessly communicate data to a central server or cloud platform for analysis and visualization.

The implementation of IoT technology in weather monitoring systems permits the deployment of a large number of sensors at a low cost, resulting in comprehensive and real-time weather monitoring. Due to their capacity to improve the precision and timeliness of weather forecasts and warnings, these systems have attracted a great deal of interest. Prior research has investigated how sensors, wireless communication technologies, cloud platforms, and mobile platforms can be integrated to enhance the collection, analysis, and visualization of data in IoT-based weather monitoring systems.

Notably, researchers have presented low-cost IoT systems that continually monitor and analyze lightning activity using specialized detectors and communication modules, allowing for real-time data storage and alarms [16]. In addition, intelligent weather alert systems have been developed, which provide users with timely notifications via platforms such as Twitter while employing cloud-based data analysis for future weather forecasts [17]. Moreover, IoT-based data recorders employing wireless sensor networks and Wi-Fi modules have been proposed [18] for real-time monitoring and alert-based communication of weather conditions.

Solar forecasting is essential for managing and incorporating solar energy into the electrical grid. Using direct and indirect forecasting models along with PV simulation software, it is possible to accurately predict solar energy production [19]. Weather monitoring systems, especially IoT-based solutions, complement solar forecasting efforts by providing real-time data on weather conditions and assisting in the optimization of solar PV system performance. These technological advancements in solar forecasting and weather monitoring enhance the precision, timeliness, and efficacy of weather forecasts and energy management in the renewable energy sector [20].

While substantial progress has been made in renewable energy technology, there remains a notable void in the availability of advanced weather monitoring systems that can provide real-time, accurate data specifically designed for solar energy forecasting [21]. Recognizing the profound implications such a system could have on the solar energy sector; the significance of this research becomes clear. A cutting-edge and efficient system would not only surmount the limitations of existing monitoring setups but also champion a more resilient and efficient energy grid, paving the way for optimized solar energy utilization [22]. Consequently, the primary objective of this research is to develop, validate, and introduce an IoT-based weather monitoring system, aiming to set a new standard in solar energy prediction and utilization.

2. Methodology

This section concentrated on the design methodology of a weather monitoring system for solar prediction. The system's IoT component integrates sensors and devices to collect meteorological data. Temperature, humidity, pressure sensors, and rain gauge sensors are carefully placed to record relevant environmental information. The data is subsequently wirelessly sent to a central location. The system makes use of “If This Then That” (IFTTT) webhooks to enable a smooth connection with other applications and services. An IFTTT applet is created to perform an action when new sensor data is received. The received data is transmitted to a Google Sheet in real time using IFTTT's webhook capabilities.

The block diagram in Figure 1 illustrates the architecture of the project, which leverages the ESP8266 microcontroller board operating in two modes: controlling and monitoring. In the controlling mode, data from BME280 and rain gauge sensors is gathered and transmitted via Wi-Fi hotspot and wireless communication to Blynk, an IoT platform. Conversely, the monitoring mode receives the transmitted sensor data, promptly displaying it on an OLED display and the Blynk web dashboard and app. This mode enables real-time monitoring of environmental conditions. By utilizing the ESP8266 microcontroller board, the project achieves an efficient system for collecting, transmitting, and displaying sensor data, ensuring effective environmental monitoring with timely information. The integration of hardware, software, wireless communication, and IoT platforms like Blynk contributes to the overall functionality and effectiveness of the weather monitoring system.

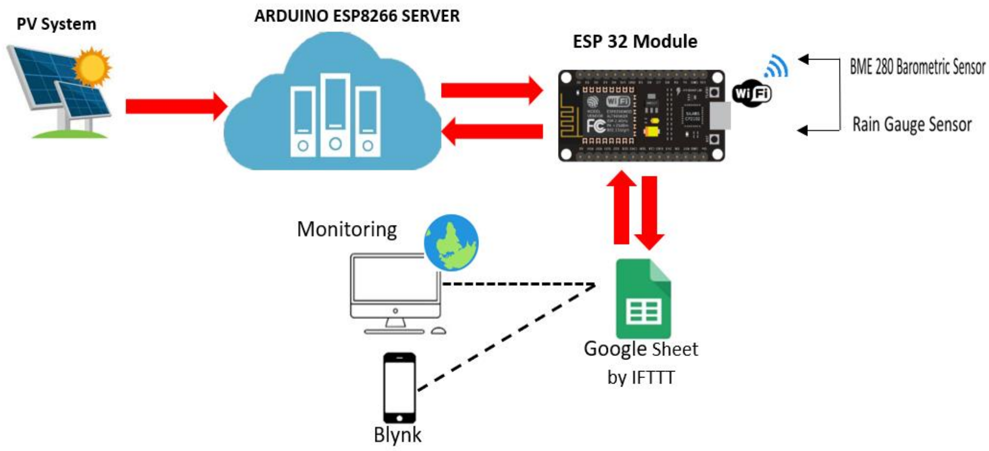


Fig. 1. Block diagram of the proposed weather monitoring system

2.1 Hardware Selection & Circuit Diagram

The selection of materials for the weather monitoring system was carried out with meticulous consideration and expertise. The NodeMCU ESP8266 microcontroller was chosen for its affordability, low-power Wi-Fi connectivity, sensor compatibility, and control capabilities, providing an economical solution with reliable wireless communication. The BME280 barometric sensor was carefully selected for its exceptional precision, quick response time, and suitability for accurate weather monitoring. To ensure precise precipitation measurement, a tilting bucket rain gauge with electronic data transmission was specifically chosen. For efficient power generation, a 10W monocrystalline solar panel was selected based on its superior performance. To regulate the power supply in a safe and efficient manner, a 12/24V 10A solar charger controller was meticulously chosen. Additionally, a 12V 7AH sealed rechargeable lead-acid battery was selected as a dependable backup power source. These carefully considered and expertly chosen materials play a pivotal role in enhancing the functionality, affordability, precision, and durability of the weather monitoring system, thereby facilitating the collection of highly accurate weather data for solar prediction and energy optimization.

The circuit connection of the weather monitoring system, which includes the BME280 barometric sensor and the tipping pail rain gauge, is depicted in Figure 2. The BME280 sensor measures temperature, humidity, and pressure, while the rain gauge uses a bucket-tipping mechanism to measure precipitation. Both sensors are connected to the ESP8266 microcontroller board in a seamless manner. Using GPIO5 (pin D1) for SCL and GPIO4 (pin D2) for SDA connections, the BME280 sensor communicates with the ESP8266. Using a one-way RJ11 terminal box, the rain gauge, which is equipped with an RJ11 male connector, is connected to the ESP8266. The positive wire is connected to the interrupt pin GPIO12 (pin D6) and the negative wire is connected to the GND port on the ESP8266 board.

In addition, the weather monitoring system is equipped with an OLED display for displaying various weather parameters and an LCD module for displaying dates and times. Collecting and transmitting sensor data to the Blynk Web Dashboard, with an exclusive display on the OLED display. In addition, the system includes an emergency alarm system consisting of a buzzer and LEDs for prompt notification of adverse weather changes. The Blynk app delivers push notifications to smartphones. The Vcc pin is connected to the 5V pin on the ESP8266 board for the I2C LCD variant, while the SCL and SDA ports are connected to GPIO5 (pin D1) and GPIO4 (pin D2), respectively. The connection scheme for I2C OLEDs is comparable, with the Vdd pin connected to the ESP8266's 3.3V pin.

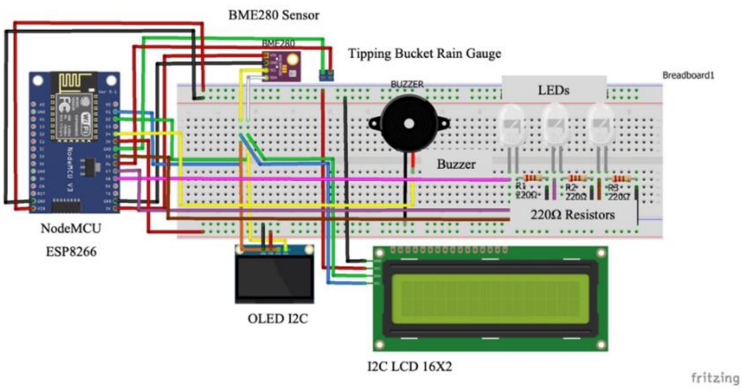


Fig. 2. Fritzing diagram of the proposed weather monitoring system

2.2 Monitoring & Data Acquisition Algorithm

This subsection describes the workflow for data collection in a weather monitoring system for solar prediction. The process flow for the weather monitoring system relies heavily on an ESP8266 microcontroller and Google Sheets through IFTTT for its operation. Using the Arduino IDE, the ESP8266 microcontroller establishes a Wi-Fi connection and retrieves sensor data such as temperature, humidity, pressure, and precipitation. This information is stored in a dictionary-like data structure and encoded as a JSON payload. Then, an HTTP POST request is sent to the IFTTT webhook URL, which causes an applet to write the data to a specified Google Sheets document.

In addition, the project investigates the possibility of integrating an IoT weather monitoring device with the Blynk Graphical User Interface (GUI). The device collects real-time data on temperature, humidity, barometric pressure, and precipitation, as well as notifications for sudden and severe weather changes. The sensor readings are displayed on an OLED screen for visualization purposes. The collected data is seamlessly transmitted to the Blynk platform, allowing users to remotely monitor and control their IoT devices using their handsets. In addition, the system is designed to respond proactively to certain meteorological parameters, such as extreme heat (temperature exceeding 40°C), high humidity (exceeding 80%), low pressure (below 1000hPa), and intense precipitation (accumulating more than 100mm in 24 hours). When these thresholds are exceeded, the system activates LEDs and a siren, alerting users quickly and clearly. This feature serves as an essential warning, especially in situations involving heavy precipitation and the potential for flooding, prompting users to take the necessary safety precautions. By integrating comprehensive monitoring capabilities into the IoT weather system, users are equipped with timely and accurate data for making sound decisions during hazardous weather conditions.

2.3 Structural Design

The weather monitoring system's structure design, depicted in Figure 3 features a 3D-printed casing made of PETG material. This casing houses the solar panel, positioned at the topmost part of the structure, along with the BME280 sensor and tipping bucket rain gauge. The strategic placement of the BME280 sensor ensures accurate measurement of temperature, humidity, and pressure, while the tipping bucket rain gauge provides reliable precipitation data. The placement of the electrical junction box, serving as a centralized unit for the NodeMCU ESP8266, resistor, buzzer, LEDs, LCD, and OLED is also illustrated accordingly. This arrangement protects the electronic components from environmental factors, ensuring their functionality and longevity. The adjustable pole, constructed from a sturdy hollow steel bar, allows for height adjustment between 1.5 and 2 meters, facilitating precise positioning of the sensors and solar panel. The 3D-printed casing provides waterproofing and durability for the solar charge controller and lead-acid battery, while the electrical junction box safeguards the remaining components. Together, these design elements offer a comprehensive solution for accurate and reliable weather monitoring.

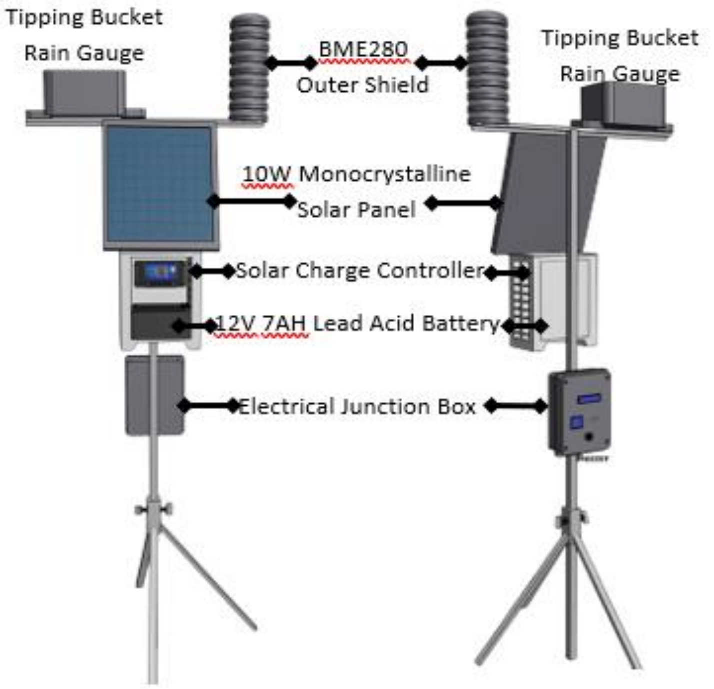


Fig. 3. 3D structural design of the weather monitoring system

2.4 Weather Monitoring System IoT Dashboard

The foundation of our weather monitoring system is an advanced IoT dashboard tailored specifically for solar predictions. The Blynk platform was selected for its intuitive interface, broad module library, and IoT compatibility. Figure 4 illustrates the dashboard with eight distinct displays. Four gauge displays represented temperature (range: 0 to 100°C), humidity (0 to 100%), pressure (0 to 1013.25 hPa), and precipitation (0 to 100mm). A super chart widget was incorporated for data trend analysis across intervals, ranging from one hour to three months. It aids users in decision-making and forecasting by leveraging the comprehensive meteorological data. The system integrates IoT devices with sensors for temperature, humidity, pressure, and rain to ensure accurate data acquisition. Integration with the Blynk platform was seamless, supporting multiple protocols, including Wi-Fi and

Ethernet. To enhance data security, features like authentication tokens and network credentials were implemented.

Fig. 4. Weather monitoring system IoT dashboard

3. Results Analysis and Discussion

This section demonstrates the outcomes from the project's developmental phase, data aggregation, and performance assessment related to the developed system tailored for solar prediction. The acquired data undergoes meticulous scrutiny to shed light on the efficacy and accuracy of the system. Through comparison of the actual performance metrics against anticipated values across diverse timeframes, potential discrepancies and fluctuations throughout a given day are identified. The obtained data is compared with simulations produced by PVSyst [23] for a rigorous validation. Additionally, the robustness of the alarm system in tracking crucial weather anomalies is also evaluated. Following this, a comprehensive discourse on the findings is undertaken, pinpointing potential enhancements, and proposing strategies to bolster the system's overall efficiency.

3.1 The Developed Prototype

The prototype, as illustrated in Figure 5, showcases a carefully engineered system that prioritizes both user experience and data accuracy. One distinct feature of the prototype is its telescopic tripod, which can be adjusted to heights between 1.5 to 2 meters. This flexibility permits users to choose an installation point tailored to environmental conditions and individual needs. The tripod, made from hollow steel, ensures robustness and stability against diverse weather challenges.

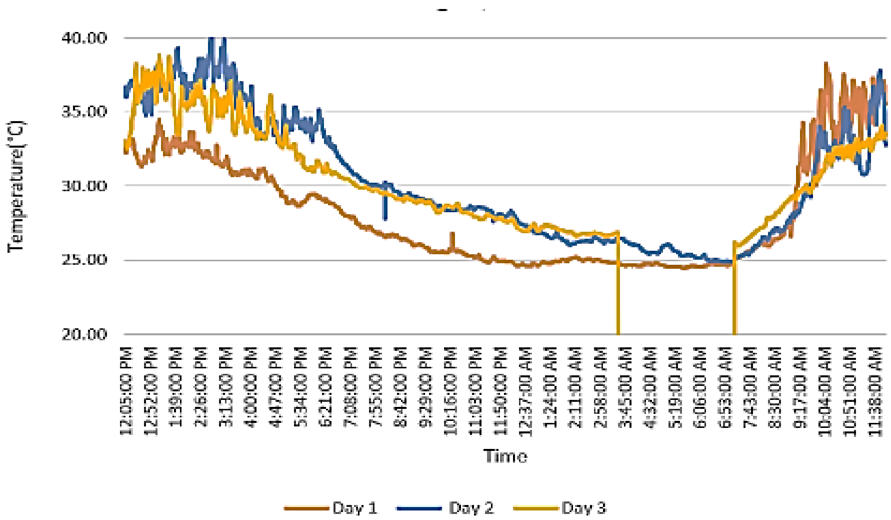
The BME280 sensor, which measures temperature, humidity, and pressure, is nestled within a protective circular shield. This design minimizes the sensor's direct exposure to external influences like rain and intense sunlight, thus guaranteeing data precision. The design also includes a tipping bucket rain gauge in proximity to the BME280 sensor, facilitating concurrent precipitation readings. This setup underscores the system's all-encompassing weather tracking ability. The prototype’s electronic elements reside in a 3D white protective casing, which shields pivotal components like the solar charging controller and battery from detrimental weather conditions.

Furthermore, an electrical junction box is incorporated to house various electronics, including NodeMCU ESP8266. The box is designed to accommodate the LCD, OLED, LEDs, and alarm, ensuring timely data display and critical alerts. In alignment with sustainability objectives, the prototype employs a 10W monocrystalline solar panel for power. This integration promotes efficient use of solar energy, diminishes dependency on external energy supplies, and guarantees uninterrupted operation, making it suitable for remote areas.

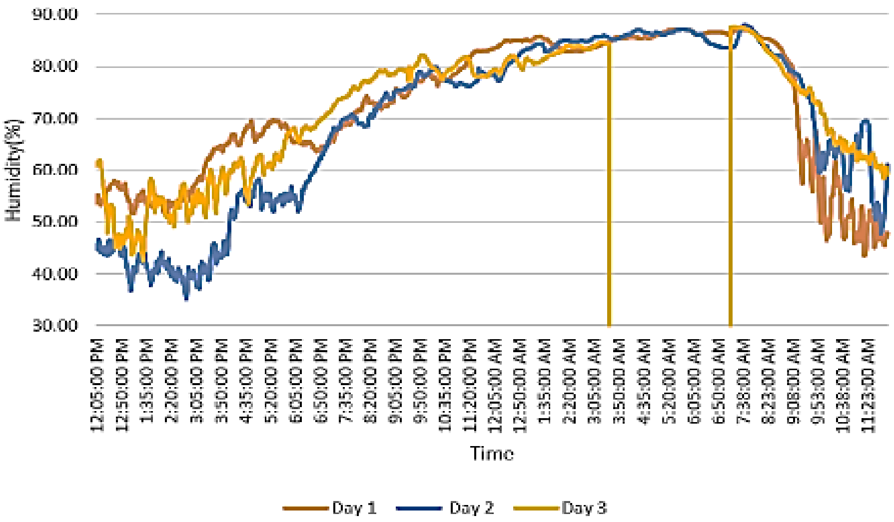
Fig. 5. The developed weather monitoring system

3.2 Data Analysis & Discussion

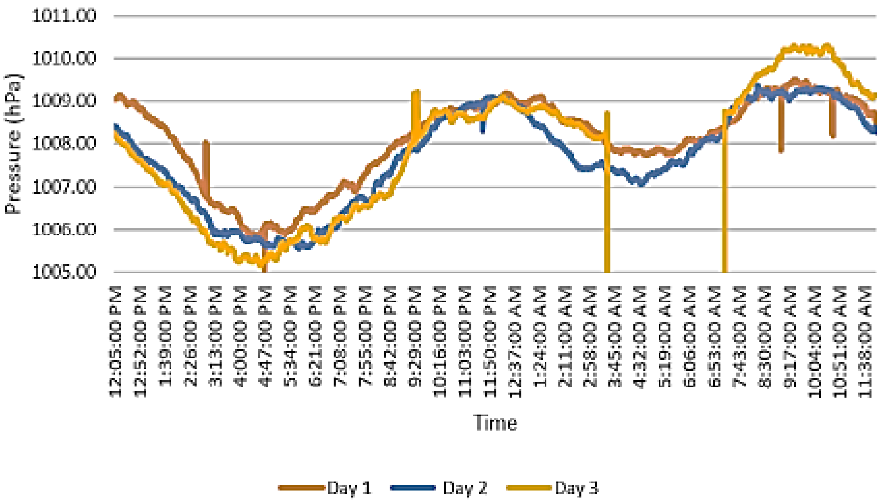
The collected data as shows in Figure 6, provides a comprehensive understanding of minute-by-minute weather patterns and their direct implications for solar prediction. This high-resolution dataset allowed for a detailed analysis of fluctuations in temperature, humidity, pressure, and precipitation, enabling a deeper comprehension of their impact on solar energy generation. The fine-grained temporal resolution of the data was crucial in capturing rapid changes and short-term weather phenomena that significantly influence the accuracy of solar prediction models.



(a)



(b)



(c)

Fig. 6. 24-Hours meteorological parameters: temperature (a), humidity (b) and pressure (c) monitoring with 1 minute resolution.

It is important to note that there is a temporary loss of connectivity that occurred during the data collection period, resulting in loss of data between approximately 3:48 AM and 7:15 AM on the last day. However, the overall dataset remains robust and provides valuable insights into the intricate temporal variations of weather patterns. Such data acquisition helps anticipate cloud formation and its impact on solar radiation. In addition, temperature variations may influence solar panel efficiency, highlighting the need for monitoring and forecasting. Monitoring air pressure assists in predicting cloud cover and solar irradiance, while the absence of precipitation ensures uninterrupted solar radiation exposure for optimum energy output.

Next, the acquired temporal meteorological data are subsequently compared with PVsyst, a renowned photovoltaic system simulation software that serves as an industry benchmark for modeling and simulating solar systems. This comparison validates the practical effectiveness of the monitoring systems and provides a context for their accuracy and reliability. Figure 7 reinforces the findings by demonstrating a strong correlation and consistency between the weather monitoring system and PVsyst in one of the meteorological parameters namely humidity. This indicates the weather monitoring system's ability to provide accurate data for solar prediction. Future efforts should focus on incorporating additional weather characteristics and exploring alternative sources or models to further enhance the system's performance in solar prediction.

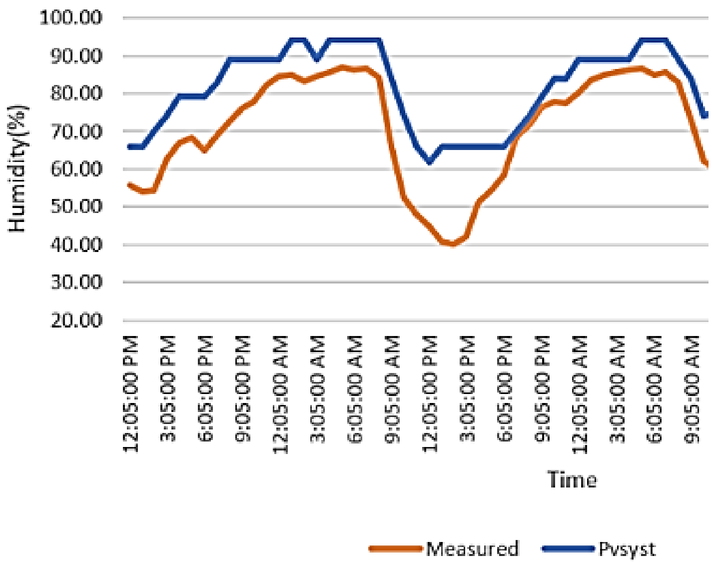


Fig. 7. Example of comparison between measured humidity (%) time series data with the PVSyst Software.

In order to justify the data quality of the time series acquisition in this prototype, the time series comparison has been carried out considering the availability of the PVsyst data set. The error ε has been identified as mean ε_{mean}, standard deviation ε_{std} and root mean square ε_{rms} as presented in Table 1 which compares the time series results for temperature and humidity. As expected, the error result (%) clearly shows an excellent performance of the time series acquired by the developed prototype.

Table 1
Comparison results of the temperature & humidity time series between measured and PVSyst (ε in %)

Parameter	ε_{mean}	ε_{std}	ε_{rms}
Temperature	-4.95	8.88	10.11
Humidity	17.43	15	22.89

3.3 Notification and Alarm Features

The use of IoT technology and the Blynk platform in this project proved highly effective for real-time monitoring of weather conditions. By integrating Blynk, the prototype established seamless communication with the user's mobile device, enabling quick notifications whenever monitored parameters exceeded predefined criteria. This ensured prompt alerts for potentially hazardous weather conditions. Push notifications played a crucial role, with the system issuing notifications to the user's device immediately when a metric like humidity surpassed a threshold. The frequency of these notifications, as depicted in Figure 8 can be adjusted accordingly with respect to the threshold of humidity levels required. It should be also noted that Blynk has a limitation of 100 notifications per day, which only for the prototype application. In fact, such limitations, the prototype also included additional hardware components such as a buzzer and LEDs which aim to serve as an alternative mechanism for meteorological parameters variations above/below the thresholds.

Fig. 8. Example of alarm notification on Blynk when meteorological parameters above/below the thresholds set.

The prototype's built-in alarm system depicted in Figure 9, ensured timely notifications, enabling users to take appropriate measures to mitigate potential risks or impacts caused by adverse weather conditions [24]. The overall performance evaluation confirmed the alarm system's effectiveness in providing timely notifications and monitoring weather conditions accurately.

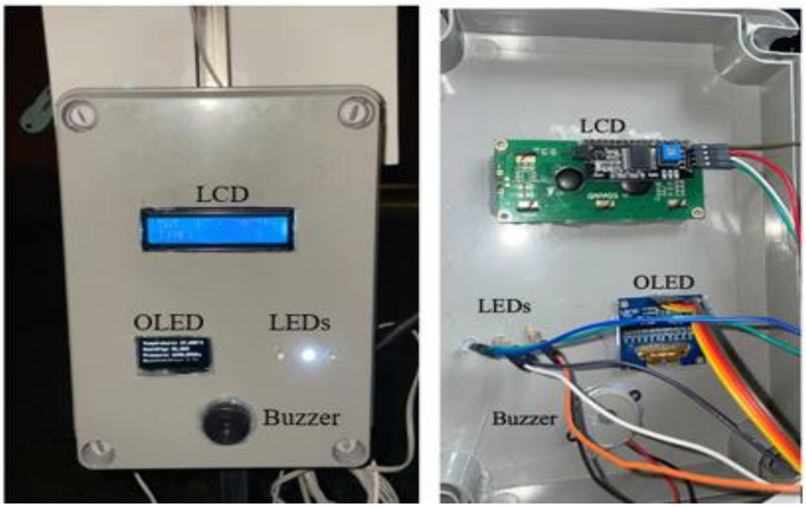


Fig. 9. Alarm & notification features on the proposed weather monitoring system

4. Conclusions

In conclusion, the developed IoT-based weather monitoring system, designed specifically for solar forecasting, has set a new standard in capturing precise and dependable data concerning key environmental parameters like temperature, humidity, pressure, and precipitation. The adept integration of the BME280 sensor with the tipping pail rain gauge facilitated accurate measurements, which have been corroborated through methodical validation against the PVsyst software's meteorological data. Real-time monitoring and data transmission, facilitated by the Blynk platform, underpin this system's exemplary performance. The robust accuracy, instant data access, and vast scalability of this system position it as a pivotal tool in solar forecasting. It not only supports the ongoing advancements in renewable energy technologies but also charts a path towards a more sustainable energy future.

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