

INTERNET OF THINGS FOR MONITORING AND OPTIMISATION OF STAND-ALONE SYSTEMS IN RURAL AREA: AN EXPERIMENTAL CASE

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Abstract

The integration of the Internet of Things into the renewable energy sector establishes a communication network that interconnects sensors across diverse renewable energy resources and corresponding software for seamless data exchange and functional operations. Rural areas, particularly those relying on stand-alone renewable energy systems, face significant challenges in effectively integrating and optimising renewable energy sources. These challenges include the need for continuous monitoring of energy production and consumption, accurate forecasting of electric energy usage, and enhancing the overall efficiency of renewable energy power generation. This study addresses these challenges by employing advanced networking and data processing tools to enhance the integration and optimal utilisation of renewable energy sources. The objective is to implement an improved wireless monitoring system through IoT protocols, fostering efficient information access and automated workflows. The proposed system encompasses a solar panel, charge controller, battery, inverter, load, and an IoT system for real-time monitoring of electrical parameters. The study results demonstrate exceptional accuracy, achieving 98.6%, affirming the effectiveness of the IoT-enabled monitoring system in optimising power management.

Keywords: Hybrid renewable systems; Internet of Things; Power management optimisation; Renewable energy; Wireless monitoring.

1. Introduction

The demand for energy, a fundamental catalyst for development, continues to escalate globally, driven by factors such as population growth, technological advancements, and geopolitical dynamics [1, 2]. Historically, conventional energy sources like coal, natural gas, petroleum, and nuclear power have served as primary means of electricity generation. However, these conventional reservoirs have been dwindling over time, prompting a shift towards renewable energy sources characterised by sustainability and cleanliness. Renewable energy, including solar and wind power, represents a viable solution to address the challenge of energy sustainability [3, 4].

This study is centred on exploring the integration of wind and solar energy resources. The concept of hybrid power plants, which combine multiple renewable energy sources, emerges as a promising solution to mitigate fuel scarcity and electricity deficits, particularly in rural and remote regions [5]. By harnessing the synergies between wind and solar power, hybrid systems offer the potential for continuous energy supply with enhanced efficiency [6, 7]. Such integrated systems capitalise on the complementary nature of wind and solar energy, optimising the utilisation of individual component capacities to maximise overall output.

The monitoring system is designed to meet two essential objectives: remote monitoring and anomaly detection. Monitoring the system's conditions is crucial for analysing and assessing the performance of hybrid renewable energy systems, ensuring their effective and efficient operation. Remote monitoring capabilities enable real-time access to system status and research data, facilitating a comprehensive study of the hybrid power plant's performance. With this information at hand, proactive measures such as preventive maintenance can be implemented to enhance system performance and prolong its operational lifespan [8]. By maintaining system efficiency and reducing total operating costs through timely interventions, the monitoring system contributes to the sustainable and economical operation of the hybrid renewable energy system.

The advent of wireless sensor networks contributes to innovations such as the Internet of Things IoT and cloud services, which incorporate and track the status of things in a very efficient manner. IoT is a new technology linking different things, objects, or devices through the Internet [9]. The IoT is the inter-networking of physical devices or objects embedded with network connectivity, enabling these objects to collect and exchange data [10]. The IoT network gathers data from physical objects such as sensors and actuators and transmits it over the Internet, allowing access to system information anywhere at any time. Smart devices such as smartphones, laptops, and portable devices can connect to IoT devices via the Internet. The IoT has gradually achieved various wireless sensor network sensors, such as GSM, GPRS, Wi-Fi, microcontrollers, and others [11].

Ensuring the stability of the infrastructure is imperative when incorporating IoT. The robustness of the IoT device must be safeguarded to prevent potential exploitation by malicious entities, which could compromise the integrity of the entire system. Suppose the security infrastructure is effectively managed and seamlessly integrated with the Internet of Things. In that case, life can be considerably simplified and more convenient, particularly in a world increasingly dependent on technology.

Several studies have been conducted in the implementation of power generation remote monitoring systems, such as monitoring a locally generated system using a cloud-based system, simulation of an IoT-based solar energy monitoring system, monitoring a solar-wind hybrid system using ADAFRUIT cloud, and plant monitoring using free, libre open-source software (FLOSS). This study discusses the different systems and their characteristics.

A cost-effective method for remotely monitoring solar plant performance by the inclusion of IoT was used [6]. The method can assist with plant maintenance, problem diagnostics, and real-time monitoring, while a PV/T facade system and IOT monitoring cloud platform were combined with monitoring the PVT system in real time and online [8]. An online-based monitoring system was proposed to study various cloud platforms as data transmitters [9, 10]. The method used Zig-bee wireless nodes and was developed and interfaced with each power source to transmit data to the master controller. The master controller was equipped with an ethernet shield to send data to cloud servers.

Data collected by the master controller through the Zigbee node was sent to the cloud platform, i.e. to Thing Speak. Patil used Proteus Professional as simulation software to study the system's behaviour with different variables [11]. The method is used for validating the system circuit virtually and connecting it to Wi-Fi and ESP8266 for remote monitoring. The sensors attached to the system sense the conditions, and Arduino analyses the data from these sensors about parameters. The data is then uploaded to the Adafruit cloud, which provides various statistical tools in a single click.

The data of parameters are moved over the cloud [12]. A monitoring system for a hybrid power plant based on Free Libre Open-Source Software (FLOSS) was the focus [13]. The system was built consisting of components of network and internet access. The IoT server software is Thing Speak and has a Free Libre Open-Source Software license, GNU GPL 3. Data delivery and requests on Thing Speak using a simple HTTP request can also be used in subsections. The style named "I3M-Subsubsection-Headings" for the heading of the subsection is used.

The HRES architecture proposed by Eltamaly et al. [14] consisted of a wind turbine, a photovoltaic system, a battery storage system, and a diesel generator. There are four parts to this architecture: power, data acquisition, communications network, and application layers. HRES communication models are determined by the IEC 61850 standard because there are multiple communication technologies and no standard communication model. Various categories can be used to categorise electrical parameters. A hybrid energy management system (EMS) in smart homes was proposed by Rajesh et al. [15].

A hybrid wrapper is proposed that combines Sailfish Optimizer with Adaptive Neuro-Fuzzy Interference System. It is commonly known as SFOANFIS. The power and resources of distribution systems are optimally managed. A cloud-based communication system is used for DS. Each appliance is connected to the cloud IoT with its IP address to reduce the growth of demand response (DR) in home emergency medical services (HEMS). Demand response data is collected from every household appliance. A SFOANFIS method is used to manage data.

Additionally, DS-based IoT networks increase their flexibility and optimise resource usage. It fulfils both energy demand and supply. In comparison with

several existing algorithms, including ANFIS and advanced slap swarm optimisation algorithms (ANFASO), Sailfish Optimizer, and squirrel optimisation using gravitational search aided neural networks (SOGSNN). Smart grid technology must be implemented and advanced to reinforce smart energy systems. Innovations in technology, such as IoT, have a significant impact on the energy sector. Many aspects of the sector are now using IoT, including transmission, distribution, power generation, renewable energy integration, and load management. Smart energy systems are being implemented in four main areas with IoT: business, smart energy applications, data transmission, and IoT in business [16].

Talaat et al. [17] explored the implementation of a hybrid-cloud architecture to enhance the monitoring and management of power systems within smart grids. The study focuses on the integration of both public and private cloud environments to optimise data processing, ensuring high efficiency, scalability, and reliability. The authors highlight how this hybrid-cloud approach can manage large volumes of data generated by smart grid sensors, providing real-time insights and improved decision-making capabilities. This system is particularly beneficial for sustainable urban environments, offering a robust solution for the challenges associated with smart grid data management and monitoring. Kulkarni et al. [18] investigated the application of cloud computing technologies to enhance the real-time monitoring and control of grid power systems.

The study emphasises the benefits of cloud-based solutions in managing the complexities of power grids, including improved data storage, processing capabilities, and accessibility. The authors demonstrate how cloud computing facilitates the integration of various grid components, enabling more efficient and reliable power system operations. Their findings underscore the potential of cloud computing to revolutionise grid management by offering scalable and flexible solutions that cater to the dynamic needs of modern power systems.

Despite advancements in renewable energy integration, a significant gap exists in the efficient real-time monitoring and control of stand-alone systems, particularly in remote areas with limited infrastructure. Current systems often lack robust communication networks capable of handling the complex interactions between various components of renewable energy setups. This challenge, coupled with the need for reliable data processing and energy forecasting, hinders the optimisation of energy generation and storage systems in isolated regions.

The objective of this study is to develop and implement an advanced IoT-based wireless monitoring system that facilitates real-time data acquisition and control for stand-alone renewable energy systems. The novelty of this research lies in the integration of IoT protocols with enhanced data processing algorithms tailored for remote and off-grid applications, addressing the unique challenges of rural energy management. By focusing on electrical parameters such as voltage, current, power, and energy efficiency, this study investigates the performance of a system composed of solar panels, charge controllers, batteries, inverters, and loads. The scope of the research covers variable ranges such as system load conditions, energy storage capacities, and communication latency, providing a comprehensive evaluation of system efficiency under different operational scenarios.

2. System Design and Experimental Setup

The solar wind hybrid monitoring system consists of three primary components: network and internet infrastructure, IoT server elements, and sensor units. The overall configuration of the current monitoring system is illustrated in Fig. 1. The IoT nodes require essential software and basic control processes for operation. These nodes utilise "NodeMCU8266" modules to collect sensing data, which is then transmitted either between nodes or directly to the node-to-node server. Concurrently, the cloud server, equipped with an IP address, is connected to the Internet, enabling it to receive and relay information. The server is responsible for aggregating, processing, analysing, and storing all sensor data via Wi-Fi connectivity. Additional functionalities and software enhancements are being developed by leveraging internet resources. The IoT cloud server serves as a centralised control hub, continuously monitoring the transmitted parameters gathered from the "Wireless Sensor Network" (WSN). With internet connectivity, administrative personnel can access the server remotely from any location.

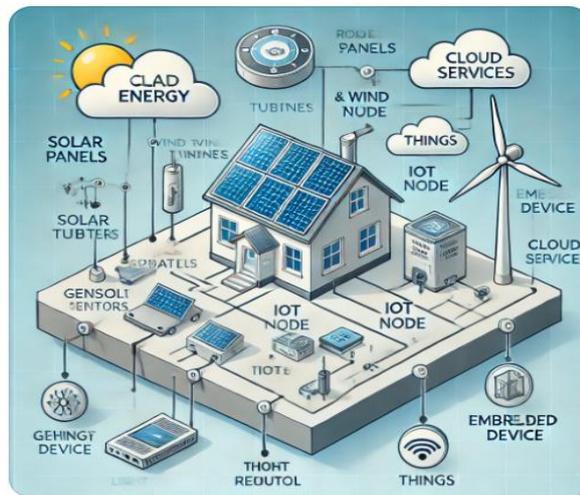


Fig. 1. IoT devices architecture.

The IoT server's role extends beyond mere data reception and transmission. It serves as a comprehensive data management platform, employing advanced analytics algorithms to extract valuable insights from the collected sensor data. These insights enable proactive decision-making and facilitate system optimisation in real time. Moreover, the server's internet connectivity facilitates seamless integration with external databases, cloud-based services, and third-party applications, enhancing its functionality and interoperability. Additionally, efforts are underway to develop user-friendly interfaces and dashboards, providing stakeholders with intuitive tools for monitoring system performance and configuring parameters remotely. Overall, the solar wind hybrid monitoring system is evolving into a sophisticated and versatile solution for monitoring and managing renewable energy resources, offering scalability, flexibility, and enhanced control capabilities.

The proposed technique continuously monitors the energy generated by solar panels. Sensors integrated into the device detect environmental conditions, and

Arduino processes the data collected from these sensors, analysing various parameters. Equipped with a Wi-Fi module, the device establishes a connection with mobile devices. Real-time data for many of these parameters is uploaded to the server, providing users with access to these dynamic parameters. The microcontroller chip integrated with all essential sensors, components and analysed data is NodeMCU8266. The microcontroller has three sensors that detect various factors that affect the whole device. These sensors are linked to the solar panel, and a battery bank is connected to a DC-to-DC converter, which lowers the voltage value transmitted from the voltage sensor.

Figure 2 depicts the systematic flow of operations within the entire system. It commences with the Arduino, initiating the connection process with the Internet. Upon successful establishment of the connection, the system proceeds to generate an IP address. In the event of a connection failure, the system reverts back, displaying an error message. Subsequently, input data is collected from various sources, including the solar panel and other attached sensors. This data is then transmitted to the microcontroller for processing. Once processed, the data is relayed to a cloud server for storage and further analysis. Users have the convenience of accessing this data from their workstations or mobile devices. All stored data is made readily accessible through a web server interface, facilitating seamless retrieval and utilisation.

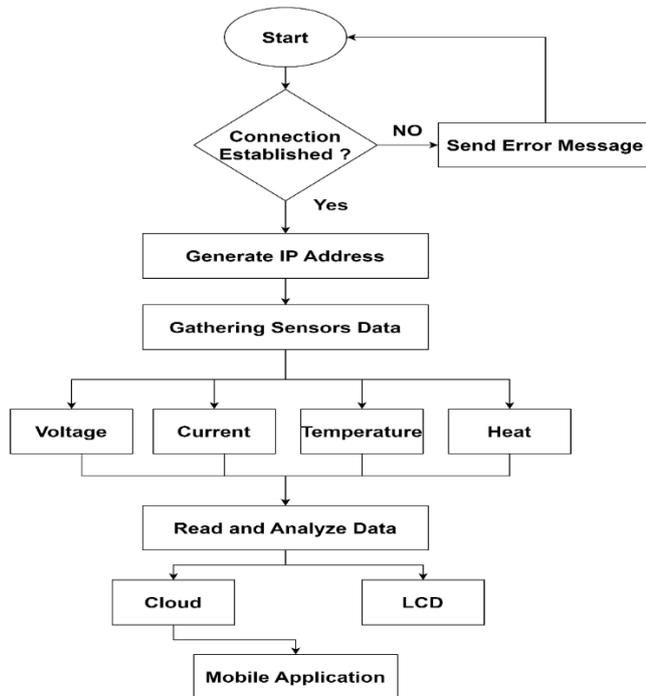


Fig. 2. Proposed hardware design.

The system's connection process involves a series of checks and protocols to ensure robust and reliable connectivity. In case of connectivity issues or errors, the system employs automated error-handling mechanisms to promptly address and

rectify any issues. Additionally, advanced encryption and security protocols are implemented to safeguard the integrity and confidentiality of the transmitted data. Moreover, the cloud server serves as a central repository for storing and managing vast amounts of sensor data, leveraging scalable storage solutions to accommodate future expansion and increased data volumes. Furthermore, the web server interface is continuously optimised to provide an intuitive and user-friendly experience, with features such as customisable dashboards and real-time data visualisation tools enhancing usability and accessibility for users. Overall, the process flow depicted in Fig. 2 underscores the seamless integration and functionality of the system, ensuring efficient data collection, processing, and accessibility for users.

The three sensors involved in the monitoring system are the voltage sensor, load voltage and current sensor, and temperature and humidity sensor. The sensors are connected to the NodeMCU8266 board. A battery is also attached between the load voltage, current sensor, and DC to DC converter. The battery will be the power source to power up the microcontroller. Figure 3 depicts the circuit diagram of the proposed approach for integrating the device.

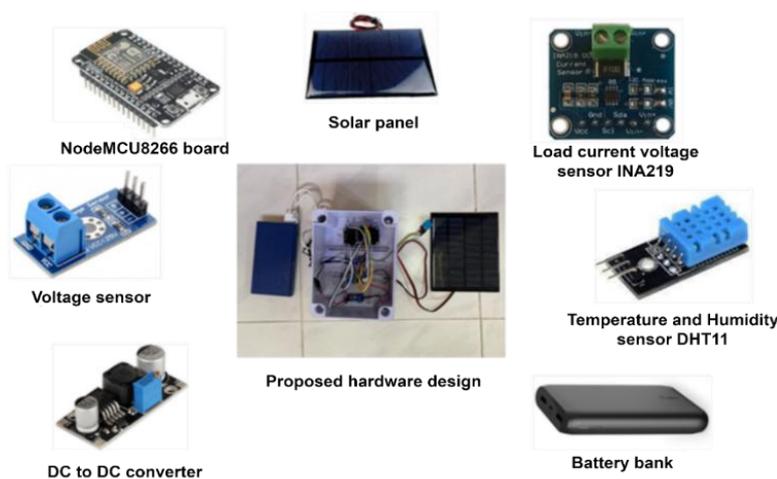


Fig. 3. Proposed hardware design.

The following components were used to build the prototype underlying system, as shown in Fig. 3.

The first component is NodeMcu8266 from Fig. 3. NodeMCU is an open-source "Lua-based firmware and development board" specially targeted for IoT-based applications (Components10, 2020). It has 16 GPIO pins, 4 SPI pins, 2 UART pins and an I2C PIN. NodeMCU can be powered using a "Micro USB jack and VIN pin". It can be easily programmed with Arduino IDE since it is easy to use. All it needs is the Arduino IDE and a USB cable.

The second component, as depicted in Fig. 3, is the voltage sensor. Specifically designed to read the voltage input produced by the solar panel, this sensor generates an analogue voltage signal. It is an integral component connected to NodeMCU8266.

The third component is the DC-to-DC voltage converter from Fig. 3. A DC-to-DC converter is an electronic circuit that converts a DC source from one voltage level to another desired level. This voltage converter is needed to convert the voltage value to match the voltage value accepted by the battery bank.

The fourth component is the load voltage-current sensor from Fig. 3. It is the second component linked with NodeMCU8266. It can measure both current and voltage in an external system independently. This component is needed to read the current and voltage values inside the battery bank at that time.

The fifth component is the temperature and humidity sensor DHT11 from Fig. 3. DHT11 "Digital Temperature and Humidity Sensor" is a compound sensor with calibrated digital signal output. The sensor includes a resistive humidity-sensing component and an NTC temperature-sensing component. This sensor measures the temperature and humidity of the surrounding solar panel. This is the third component linked to NodeMCU8266.

The sixth component is the battery bank; the power bank is used to store energy. The battery is also used to power up the microcontroller. The power bank shown in Fig. 3 is considered a load, and another sensor will measure the current and voltage. The last component is the solar panel, as shown in Fig. 3. The solar panel chosen is monocrystalline silicon. The solar panel will convert solar energy into electrical energy. Monocrystalline silicon PV is claimed to be the most efficient and durable among other materials.

3. Result and Discussion

A mobile application has been developed to interface with the cloud, enabling users to access real-time data and receive instant updates on system performance and parameters. This application serves as a convenient tool for users to monitor and manage the hybrid renewable energy system remotely, providing seamless access to critical information at their fingertips. Through the mobile application, users can view comprehensive dashboards, graphical representations, and detailed analytics derived from the sensor data stored in the cloud. Additionally, the application offers interactive features, allowing users to customise their preferences, set alerts for specific events or thresholds, and remotely control system parameters as needed. Moreover, the mobile application is designed with user-friendly interfaces and intuitive navigation, ensuring ease of use and accessibility for a wide range of users.

Moving forward, continuous enhancements and updates to the mobile application are planned, including integration with emerging technologies such as "augmented reality" (AR) for immersive visualisation experiences and enhanced user engagement. Overall, the mobile application serves as a powerful tool for enhancing user experience and facilitating efficient management of the hybrid renewable energy system. It can be viewed through an application called BLYNK. The application can be installed on a mobile device, PC, or laptop. The data from the system may be viewed immediately on any device the user prefers.

Users have the flexibility to opt for either light mode or dark mode when viewing parameters. As illustrated in Fig. 4, the application is presented in dark mode. Additionally, users can customise which parameters they wish to display. For this project, load voltage, current, and solar panel voltage were selected. Figure 4(a) shows a super chart at the bottom of the graphical user interface.

The super chart is a live chat feature provided by the BLYNK application, allowing users to analyse the values generated by the system. Results agree with [19]. Figure 4(b) illustrates the impact of shading on data monitoring. Here, shading simulates scenarios where solar panels are obstructed from receiving solar irradiation. When shading occurs, there is a noticeable drop in voltage readings, indicating reduced solar PV performance. However, once the shading is removed, voltage readings return to normal levels. The visualisation presented in the super chart is displayed in light mode for clarity.



(a) Monitoring result on BLYNK application

(b) Display of data monitoring with shading effect.

Fig. 4. Monitoring and data display.

Subsequently, an experiment was conducted to assess the effect of soiling on solar panel performance. Dust particles were deliberately applied to certain areas of the panel to mimic real-world conditions. In Fig. 5(a), a combination of shading and soiling anomalies can be observed, intentionally distributed unevenly to replicate natural occurrences. This approach aims to simulate scenarios that may occur in practical settings. Figure 5(b) depicts the graph when dust accumulates on the solar panel. The presence of dust reduces the panel's efficiency by obstructing incoming solar rays, leading to a decrease in power output. Despite the dust, voltage readings can still be obtained, albeit with fluctuations due to the uneven distribution of dust particles. This fluctuation reflects the impact of anomalies on energy harvesting by the solar panel. The graphical user interface offers users the flexibility to switch between light and dark modes for optimal visibility.

The anomalies experiment was conducted to observe graph patterns in scenarios where errors occur with the solar panel. The results align with the findings reported in [20], confirming the reliability and consistency of the observations.

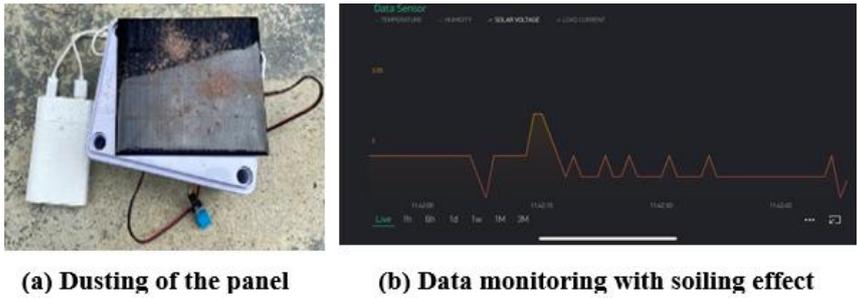


Fig. 5. Monitoring of: (a) dusting, and (b) soiling effects.

The system was validated by using the data calibration method. Each data was calibrated using other instruments like a Multimeter and thermometer. The mean, often referred to as the average, is a measure of central tendency that provides a single value representing the centre of a data set. It is calculated by summing all the values in a data set and then dividing by the number of values. The standard deviation is a measure of the amount of variation or dispersion in a set of values. It indicates how much the individual data points deviate from the mean of the data set. The accumulated result was summarised using the mean and standard deviation as shown in Equations 1 and 2 [20].

$$V_m = \frac{V_1+V_2+\dots+V_n}{n} = \frac{\sum_{i=1}^n V_i}{n} \tag{1}$$

$$S(V) = \sqrt{\frac{\sum_{i=1}^n (V_i - V_m)^2}{n-1}} \tag{2}$$

Table 1 provides a summary of sensor data calibration, represented as a percentage difference in terms of mean and standard deviation ($\mu \pm 1\sigma$ %). The standard deviation value indicates the extent to which data dispersion deviates from the mean value. Specifically, for voltage, current, and temperature, the percentage differences between mean and standard deviation values are $10.098 \pm 1.93\%$, $0.164 \pm 0.00898\%$, and $28.94 \pm 3.22\%$, respectively.

Table 1. Sensor data calibration.

Sensor Type	Percentage difference from the standard measuring instrument ($\mu \pm 1\sigma$ %)
Voltage	10.098 ± 1.93
Load Current/Voltage	0.164 ± 0.00898
Temperature	28.94 ± 3.22

Notably, the standard deviation values are smaller than their respective mean values, indicating minimal deviation of data from the mean. On average, the accuracy across all sensors is calculated to be 98.59%. These findings affirm that all sensors are functioning optimally, and the data acquisition process is both valid and reliable, ensuring the system's intended operation. Graphs depicting the data dispersion are presented below for visual reference.

Figure 6 shows the dispersion of data for the voltage sensor. The graph depicts the relationship between the theoretical value of voltage and voltage experimental value. The blue line represents data taken from the Multimeter, and the orange line

represents data taken from the voltage sensor. The difference between the two is too little. The difference between the two for each reading is less than 0.5. Therefore, it cannot be seen from the graph even when the graph's scale changes to a smaller range. The graph behaviour increases for the first hour and gradually increases for the next 4 hours. After it has passed the peak hour, the graph resides. What can be told from the graph pattern is the voltage is increased when the solar is gradually harvests the solar energy that slowly rising. After it has reached the peak intensity, the voltage value is decreased as the solar energy intensity is reduced to set in the evening. What can be confirmed from the relationship is the higher the sun irradiation, the higher the voltage value.

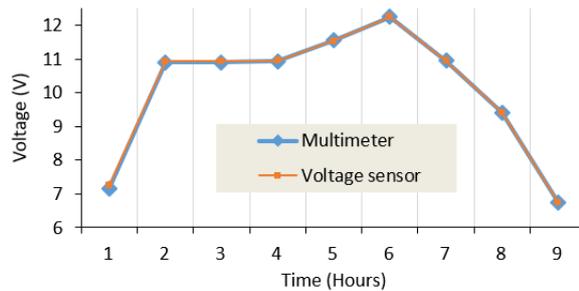


Fig. 6. The relationship between voltage theoretical value and voltage experimental value.

Figure 7 shows the dispersion of data for the current sensor. The graph depicts the relationship between the current theoretical value and the current experimental value. The blue line represents data taken from the Multimeter, and the orange line represents data taken from the current sensor. It can be seen that the reading taken from the Multimeter is a little low. The difference between the two for each reading is ranging from 0.001 to 0.10. The difference is quite extensive. The difference between the two instruments indicates that one of the two has an error. Data from the monitoring system showed a consistent reading while data from the Multimeter showed an inconsistent reading before it reached the peak hour. The Multimeter reading could be at fault here because the Multimeter used is quite old and it may cause instrument error.

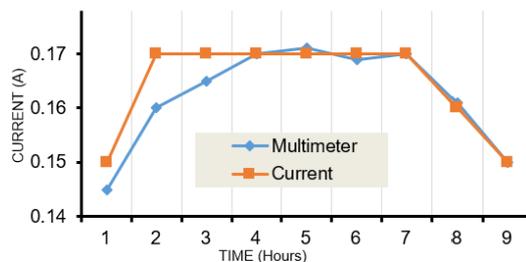


Fig. 7. Relationship between current theoretical value and current experimental value.

Figure 8 shows the dispersion of data for the temperature sensor. The graph depicts the relationship between the theoretical value of temperature and temperature experimental value. The blue line represents data taken from the thermometer, and the orange line represents data taken from the temperature sensor. There is a significant difference in the middle. The difference between the two for each reading is between 0.1 and 1.0. Therefore, there is a significant difference in the middle, where the reading is differed by 1.0. The difference is considered huge. However, from the data calibration section, it is proven that the accuracy of the monitoring system is high. Hence, the difference value can be accepted. The cause might be from the thermometer. It might have caused an instrument error.

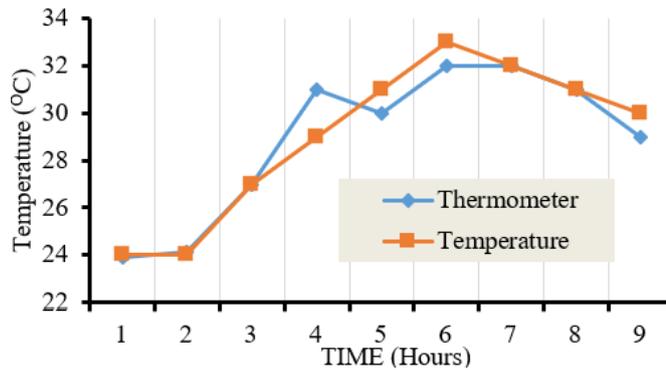


Fig. 8. Relationship between the theoretical and experimental temperatures.

From the graph, both lines increased until the peak hour at 1 PM. After that, both reside. The peak temperature is 33°C for the system and 32°C for the thermometer. The difference in temperature for peak hour is 1.0°C. The data from the monitoring system is again showing a consistent pattern. The relationship suggests that the higher the solar irradiation, the higher the temperature of the solar panel. This is because the environmental temperature is increasing due to the sun's rotation.

Based on the analysis of Figs. 6, 7 and 8, it is evident that there is a proximity in the dispersion of data points. Despite minor fluctuations observed over time, the consistently high accuracy of the sensors integrated with the PV system validates its reliability. The graphical representations within these figures support a common hypothesis: an elevation in solar irradiation correlates with a corresponding increase in voltage, current, and temperature levels, indicating a direct proportional relationship among these parameters. Particularly, the findings of this study align with the outcomes reported in previous research studies [21], thereby reinforcing the consistency and reliability of the observed trends.

4. Conclusions

In conclusion, this paper introduced a pioneering IoT-based monitoring system designed for a hybrid renewable energy system. A comprehensive review of various monitoring system mechanisms was conducted, and the experimental results derived from this study were meticulously analysed. A laboratory prototype was meticulously crafted to showcase the practicality and efficacy of the proposed system. This study incorporated not only a selection of sensors, an apt microcontroller, and real-time

algorithms for solar panel monitoring but also emphasised data access flexibility, allowing users to interact with the system from any location with an internet connection. There is immense potential for further refinement and expansion of the system created. Future enhancements may encompass the integration of a decision-making and reporting system, providing more robust insights. Additionally, the prospect of incorporating remote control capabilities into the system opens avenues for improved operational control and adaptability. The holistic vision is to evolve the IoT-based monitoring system into a versatile and intelligent platform, offering comprehensive functionalities for users in different operational contexts. The following observations are highlighted from this study:

- The average accuracy across all sensors was calculated to be 98.59%, confirming that the sensors are functioning optimally and that the data acquisition process is robust.
- The study's findings align closely with those reported in prior research studies in the literature.
- The consistent high accuracy and minimal deviation in sensor data, as demonstrated by the proximity of data points in the dispersion graphs, suggest that the PV system integrated with these sensors operates reliably.
- The direct correlation between solar irradiation and the measured parameters underscores the system's capability to accurately monitor and respond to environmental conditions, ensuring its efficient performance.

These results have significant implications for the optimisation and reliability of solar energy systems, providing a solid foundation for further research and development in this field.

Abbreviations

IoT	Internet of Things.
FLOSS	Free Libre Open Source Software.
EMS	Energy Management System.
DR	Demand Response.
HEMS	Home Emergency Medical Services.
SOGSNN	Squirrel Optimization using Gravitational Search aided Neural Networks.
WSN	Wireless Sensor Network.
AR	Augmented Reality.

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