Designing a Smart Farming Greenhouse Electrical Power Monitoring System Based on Internet of Things Technology

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ABSTRACT

This study aimed to design and implement an Internet of Things (IoT)-based electrical power monitoring system to support energy-efficient operations in a solar-powered smart farming greenhouse. The proposed system integrates key hardware components, including a NodeMCU ESP8266 microcontroller, an ACS712-05A current sensor, and a ZMPT101B voltage sensor, to measure voltage, current, and power consumption in real time. The collected data are transmitted over Wi-Fi to the Firebase Realtime Database and visualized through an Android application equipped with real-time monitoring, historical logging, and energy cost estimation features. The experimental evaluation conducted between February and April 2025 assessed sensor accuracy and overall system reliability. The results show that the voltage sensor maintained stable performance with a maximum deviation of 0.5 V, while the current sensor recorded minor discrepancies of up to 0.5 A, largely influenced by network latency and environmental interference. These quantitative findings confirm the feasibility of using low-cost IoT sensors for continuous electrical monitoring in greenhouse environments. The main contribution of this research is the development and validation of an integrated IoT-based electrical monitoring framework that enhances transparency, supports data-driven decision-making, and promotes sustainable energy management in modern smart farming systems.

Keywords-smart farming; greenhouse; internet of things; electrical; monitoring

I. INTRODUCTION

Climate change has a significant impact on agriculture and is expected to continue to affect food production both directly and indirectly [1, 2]. Increased average temperatures, changes in rainfall patterns, increased changes in temperature and rainfall patterns, changes in water availability, frequency and intensity of extreme events, sea level rise and salinization, disturbances in ecosystems, will have major impacts on agriculture, forestry, and fisheries [3]. The extent of these impacts depends not only on the intensity and period of the change, but also on the combination of the two, which is more uncertain and depends on local conditions. These conditions can affect food sources over time, so ways to improve food security are essential [4].

In recent years, IoT technology has been widely used to solve agricultural problems, especially those related to climate change, as well as decision support systems to determine more accurate agricultural processes [5]. After processing the data obtained from the sensors, the system can provide estimates to help farmers make smarter decisions for agricultural processes [6].

In [7], the use of IoT for Climate-Smart Agriculture (CSA) was investigated, with a particular focus on smart irrigation systems. This study used solar panels as an energy source in the development of smart irrigation systems. Distributed solar energy resources can be operated, monitored, and controlled remotely. The design of an IoT-based solar energy system for smart irrigation is critical for areas around the world that are facing water and electricity shortages. The proposed system used a single-board System-On-a-Chip (SOC) controller with WiFi connectivity and a connection to solar cells to provide the required power. The controller read soil moisture, air humidity, and temperature sensor data, and then issued the appropriate actuation commands to operate the irrigation pump.

In [8], the focus was on the cultivation of tomato plants (Solanum lycopersicum) in Algeria, a country characterized by diverse climatic conditions between its northern and southern regions. This study identified that most existing greenhouse systems were only capable of monitoring one or two environmental parameters, such as temperature or humidity, while optimal plant growth requires simultaneous control of multiple factors, including air temperature, soil moisture, light intensity, and water availability. Therefore, the proposed system was designed to automatically control several environmental parameters at the same time, to improve energy efficiency, conserve water, and ensure better crop quality and productivity. The results demonstrated that the application of fuzzy logic in greenhouse control systems provides significant advantages, as it can effectively handle uncertainty and variability in environmental conditions without the need for complex mathematical models.

Since the volume of data collected by various IoT sensors in smart agriculture applications is increasing, the storage and processing of big data for agricultural applications is becoming a great challenge. In [9], three transformation-based lossy compression mechanisms were applied to five weather datasets collected with different sampling details from IoT weather stations. The results showed that there was a strong positive correlation between the concentrated energy of the transformed coefficients and the compression ratio and data quality. This study also showed that sampling details affected the prediction and data compression ratio. A control system was designed and developed, with data reading through sensors and access to the monitoring system through smartphones and web-based applications. The variables measured were temperature, air humidity, and soil moisture for optimal plant growth management.

Integration of IoT technology into power monitoring systems allows farmers to remotely track energy usage, analyze consumption patterns, and optimize power management strategies. By combining renewable energy systems with IoT-based monitoring, smart greenhouses can achieve higher levels of efficiency, reduce dependence on conventional electricity, and promote environmentally sustainable agricultural practices. The study in [10] presented a digital twin system to monitor crop development and power consumption in greenhouses with renewable energy sources.

In [11], the Computational Fluid Dynamics (CFD) approach was used to analyze the distribution of temperature, humidity, and airflow in a controlled agricultural environment. The background of this research lies in the need to enhance energy efficiency and crop productivity through more precise microclimate management, considering that conventional experimental methods are often inefficient and resource-intensive. This study aimed at developing a validated CFD model and providing optimization strategies for modern greenhouse systems.

Energy management is a crucial aspect of modern greenhouse operations, as electricity consumption for heating, ventilation, lighting, pumping, and irrigation systems accounts for a significant portion of total production costs and carbon footprint [12]. Recent studies have shown that energy use in greenhouses is highly dependent on structural design, local climatic conditions, and internal control strategies; therefore, precise monitoring of electrical consumption is a key step towards achieving energy efficiency and sustainability [13].

The implementation of IoT in the agricultural sector has been proven to enhance environmental monitoring accuracy, improve resource efficiency, and increase crop productivity [14]. However, the aspect of electrical energy management in smart greenhouse systems has not yet been extensively studied. Most research still focuses on monitoring plant environmental conditions, while monitoring the electrical power usage of devices such as pumps, fan motors, and lighting systems is often overlooked [15].

Unlike previous studies that focus primarily on environmental monitoring in smart greenhouses, this work introduces an IoT-based electrical power monitoring system specifically designed to analyze energy usage, sensor accuracy, and cost estimation in a solar-powered greenhouse environment. This represents a novel integration of IoT-based power measurement within smart farming infrastructure, enabling improved energy transparency and operational sustainability. The proposed system aimed to record and analyze device power consumption in real time, provide accurate data to support energy efficiency decision-making, and serve as a foundation for implementing intelligent energy management in the modern agricultural sector.

II. METHODS

A prototype was implemented in a hydroponic greenhouse located in Tambak, Ngestiharjo Village, Bantul, Yogyakarta, Indonesia. The greenhouse had an approximate surface area of 24 m² (6×4 m) and was equipped with a solar-powered energy supply system. All sensor installations, power monitoring devices, and IoT-based measurement procedures were executed within this greenhouse environment. The proposed system is a prototype designed using the ACS712-05A current sensor to detect the electric current used for greenhouse needs and the ZMPT101B voltage sensor to detect the electric voltage. The data collected is processed and stored using the Firebase database, which can then be monitored in real-time through an Android-based application.

A. *System Design*

Figure 1 shows the system design as a development flowchart.

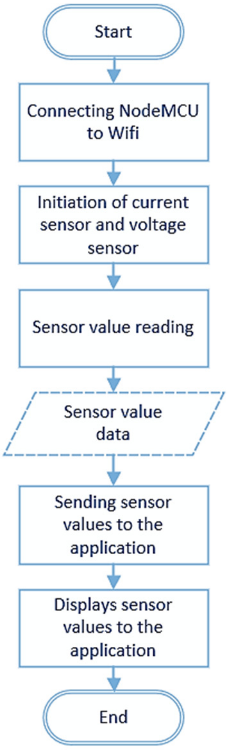

Fig. 1. System flowchart.

This flowchart presents the process of collecting and sending sensor data using NodeMCU. The steps at each stage are explained as follows.

1. Start; the process begins.
2. Connecting NodeMCU to WiFi: NodeMCU connects to a WiFi network to enable communication with the application.
3. Initiating current sensor and voltage sensors: the system initializes the current and voltage sensors so that they are ready for data collection.
4. Sensor value reading: NodeMCU reads values from the sensors.
5. Sensor value data: The collected sensor values are processed and prepared for transmission.
6. Sending sensor values to the application: The processed sensor data is sent to the application for further display and use.
7. Displays sensor values to the application: The application receives and displays the sensor readings.
8. End: the process ends.

This flowchart illustrates an IoT-based data acquisition and transmission system where NodeMCU reads sensor data, processes it, and sends it to the application for visualization.

Figure 2 presents the design of the proposed smart farming system. The system is designed to support energy-efficient smart farming operations in a hydroponic greenhouse environment. The system architecture integrates renewable energy generation, data acquisition, and remote monitoring through IoT technology. The greenhouse serves as the primary environment where hydroponic cultivation is carried out. To supply electricity for various devices such as water pumps, lighting, ventilation, and sensors, the system utilizes solar cells as the main energy source. Solar panels convert solar radiation into electrical energy, which is then distributed to monitoring and control units. This approach reduces dependence on conventional grid electricity while promoting sustainability through the use of renewable energy.

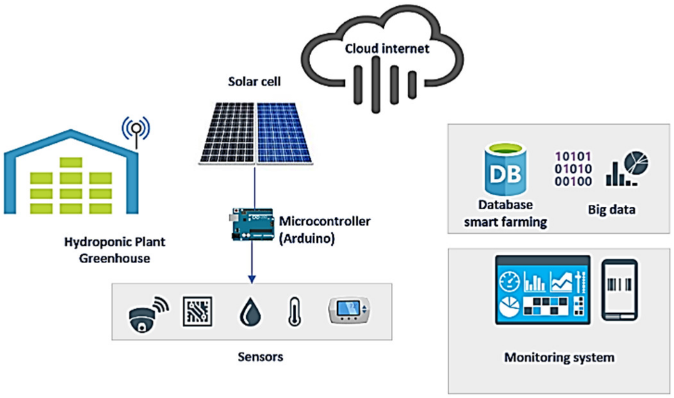

Fig. 2. Proposed smart farming system design.

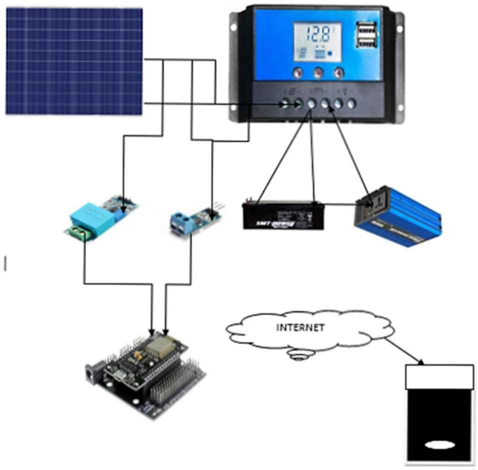

Fig. 3. Power management system design.

Figure 3 illustrates an IoT-based data acquisition and transmission system, where NodeMCU reads and processes sensor data and sends them to the application for visualization. At the core of the system lies a microcontroller (Arduino-based platform such as NodeMCU ESP8266) that functions as the central processing unit. The microcontroller receives input from multiple sensors, including current and voltage sensors (ACS712 and ZMPT101B) to monitor power usage, as well as environmental sensors, such as temperature, humidity, pH, and water level, to monitor greenhouse conditions. These sensors provide real-time data that is processed and transmitted via Wi-Fi connectivity. Figure 3 presents the hardware design of the proposed system for power management. Component details and interactions are as follows:

1. Solar Panel 100 WP: Captures solar energy and converts it into electrical power.
2. Charge controller: Manages power from the solar panel and regulates charging to the battery while distributing power to the connected load; the display on the charge controller shows the current voltage level.
3. Battery 12 V nominal voltage, 20 Ah deep-cycle lead-acid: Stores the energy collected by the solar panel for later use.
4. Inverter 300 W, input 12 V DC, output 220 V AC, 50 Hz: Converts DC power stored in the battery into AC power for use by standard electrical devices.
5. ACS712-05A, current sensor range ±5 A, sensitivity 185 mV/A, 5 V supply, analog output: Measures electrical current from DC loads.
6. ZMPT101B voltage sensor 0–250 VAC, high isolation transformer, adjustable gain, analog output: Measures AC voltage from the inverter.
7. NodeMCU (ESP8266/ESP32 microcontroller), processor 80 MHz, 4 MB flash, Wi-Fi 802.11 b/g/n, 1×10-bit ADC, 3.3 V logic: Reads data from current and voltage sensors, processes the data, and sends it to an online platform via WiFi.
8. Internet connectivity: The system sends real-time data to a cloud platform for remote monitoring.
9. User interface (cloud or web-based application): Allows users to remotely monitor the performance of the solar system via the internet, displaying real-time voltage, current, and power consumption data.

The overall function of the system is that the solar panels generate power, which is regulated by the charge controller. The battery stores excess power, while the inverter converts it to usable AC power. The sensors collect voltage and current readings and send them to the NodeMCU. The NodeMCU then sends this data to the cloud-based application via the internet, and users can remotely monitor the performance of the solar power system. This system allows efficient tracking of solar energy usage and helps optimize power management through IoT-based remote monitoring.

To maintain continuous operation when solar radiation is not sufficient, the system integrates a battery storage unit regulated by a charge controller. The battery stores excess energy generated during peak sunlight hours and supplies power to IoT devices, sensors, pumps, and monitoring units during low-light conditions. This configuration ensures uninterrupted greenhouse operations and improves the reliability of renewable-energy-based smart farming systems.

B. Hardware Design

Figure 4 displays a block diagram of the microcontroller device, current and voltage sensors, solar panels, and the data to monitor through an Android-based application.

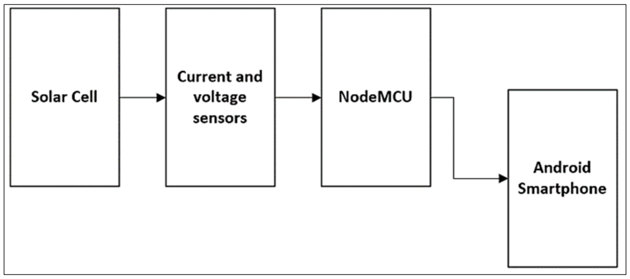

Fig. 4. Block diagram of hardware design.

Solar panels are the main power generation units in the system, which function to convert sunlight into electrical energy. The output power depends on the intensity of sunlight, temperature, and the efficiency of the panels.

The hydroponic system utilizes a 12 V DC water pump with a power rating of 18–24 W and a current draw of approximately 1.5–2 A during operation. Based on these specifications, the ACS712-05A sensor is capable of accurately measuring the pump's current consumption. The power management circuit, including the charge controller, inverter, and sensor wiring, was verified to support the pump's load. The total electrical demand remains within the supply capacity of the solar power system (100 W panel with 12 V battery storage), ensuring stable operation during irrigation cycles.

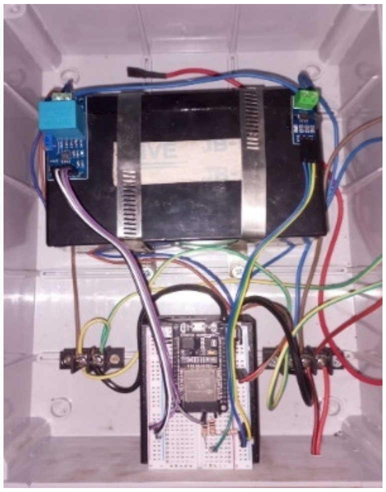

Fig. 5. Hardware circuit system.

Current and voltage sensors (ACS71205A and ZMPT10B) measure the voltage and current output from the solar panels in real-time. These sensors ensure that the system can monitor power generation and detect any inefficiencies or errors. The NodeMCU collects data from the current and voltage sensors, and processes and transmits the data wirelessly to a smartphone device, allowing for remote and real-time monitoring and control.

III. RESULTS AND DISCUSSION

A. *System Implementation*

The developed system integrates a NodeMCU ESP8266, ACS712-05A current sensor, and a ZMPT101B voltage sensor to monitor the electrical power generated from solar panels and distributed to the greenhouse. The acquired data are transmitted through Wi-Fi to the Firebase Realtime Database and displayed in an Android-based application designed using Kodular. The application consists of a welcome page, a homepage, a real-time monitoring page, and a historical data log page. This feature enables users to track energy consumption and estimate electricity costs directly from their smartphones.

B. *Black Box Testing*

System testing was carried out using the black box method, focusing on the input and output functionalities of the application. The results confirmed that all major features, including the welcome screen, the homepage, real-time sensor data visualization, and data logging, functioned correctly without syntax errors. This indicates that the system meets user requirements and can be operated effectively by end-users in a smart farming environment.

C. *Voltage Sensor Testing (ZMPT101B)*

Five tests of the ZMPT101B sensor were conducted between February and April 2024. Four out of five tests demonstrated high accuracy with no deviation between measured and reference values, while one test showed a slight delay with a deviation of 0.5 V. Overall, the voltage sensor performed reliably in monitoring the greenhouse power supply, as presented in Figure 6.

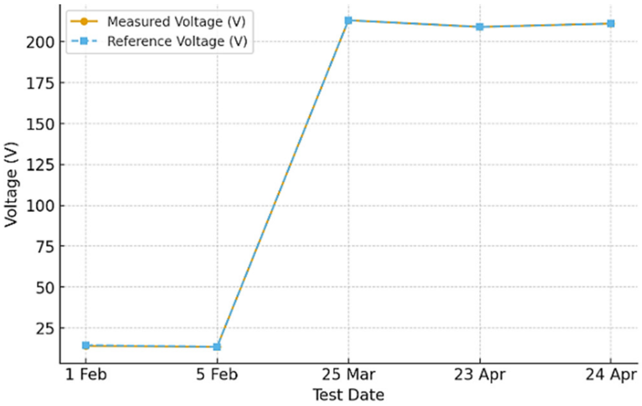

Fig. 6. Voltage sensor (ZMPT101B) accuracy test.

D. *.Current Sensor Testing (ACS712-05A)*

The ACS712-05A current sensor was also tested five times. Three tests achieved very accurate results with no deviation, while two tests indicated small discrepancies (0.1 A and 0.5 A). These variations suggest an occasional delay in data synchronization, possibly due to sensor sensitivity or internet connectivity issues. However, the sensor is sufficiently accurate for practical monitoring purposes, as presented in Figure 7. Sensor testing was conducted under ambient temperature conditions ranging from 28 to 32 °C. The load used during the tests consisted of AC appliances and a 12 V DC pump. The sampling rate of the NodeMCU data acquisition process was set to 1 sample per second before transmission to Firebase.

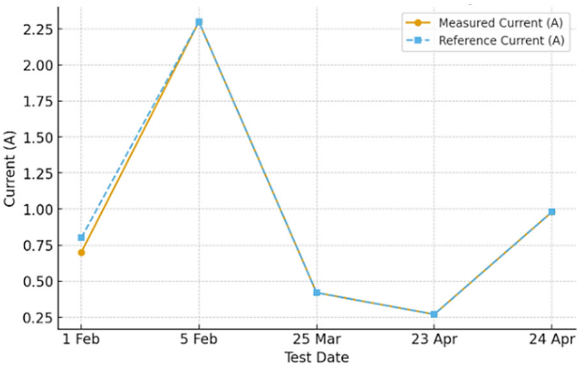

Fig. 7. Current sensor (ACS712-05A) accuracy test.

E. *System Performance Evaluation*

The integration of hardware (solar panels, sensors, NodeMCU, inverter, and charge controller) and software (Firebase and Android application) demonstrated that the system can:

- Provide real-time monitoring of voltage and current.
- Store and display historical data logs of electricity consumption.
- Estimate the electricity costs incurred in greenhouse operations.
- Support remote monitoring via Android smartphones.

This functionality is crucial for optimizing energy utilization in smart farming systems, particularly when relying on renewable energy sources.

F. *Strengths and Limitations of the System*

The system exhibits several strengths, including user-friendly access through mobile applications, remote monitoring capability, automatic calculation of power consumption and costs, and utilization of solar energy, reducing dependence on grid electricity and supporting sustainability. Despite its strengths, the system has several limitations, specifically that a stable internet connection is required for real-time monitoring. Occasional data delays of up to an hour were observed, and the system currently uses the free version of Firebase, which restricts database capacity and scalability.

G. Discussion

The experimental results validate the potential of IoT-based monitoring systems in supporting smart farming applications. The findings highlight that while the voltage sensor achieved stable and accurate performance, the current sensor requires further optimization to minimize deviations. This research confirms that IoT technology can provide farmers with fast, accurate, and transparent energy data, enabling better decision-making for resource efficiency. Moreover, the system promotes the use of renewable energy by integrating solar panels as the primary power source. This not only reduces operational costs but also aligns with sustainable agricultural practices. Future improvements could focus on integrating additional IoT devices (e.g., pumps, lighting, ventilation), enhancing the mobile application's interface, and upgrading to premium cloud services to overcome existing limitations.

The results of this study demonstrate the feasibility of integrating IoT technology into greenhouse power systems powered by solar energy. The system successfully monitored electrical parameters such as current and voltage, transmitted the data via Wi-Fi, and visualized it through an Android application. The testing confirmed that both sensors, ACS712-05A and ZMPT101B, provided sufficiently accurate measurements, enabling users to monitor energy consumption and electricity costs in real-time. From a voltage measurement perspective, the ZMPT101B sensor showed high stability and accuracy across most tests, which aligns with previous findings that this sensor type is suitable for low- and medium-voltage monitoring applications in renewable energy systems. The minor deviation observed in one test was likely due to network latency rather than sensor error, indicating that the sensor itself is reliable. This reinforces the conclusion that voltage monitoring can be effectively implemented in IoT-based agricultural systems.

The experimental findings demonstrate that the proposed IoT-based monitoring system performs reliably in measuring electrical parameters within the solar-powered greenhouse environment. The ZMPT101B voltage sensor consistently produced stable readings, with a maximum deviation of 0.5 V across five testing periods. This stability aligns with previous studies that identified the ZMPT101B as a suitable sensor for low- and medium-voltage monitoring in renewable energy systems. In contrast, the ACS712-05A current sensor showed minor fluctuations ranging from 0.1 to 0.5 A. These deviations are primarily attributed to electromagnetic interference generated by nearby electrical components, temperature variations within the greenhouse, and occasional network latency during Wi-Fi data transmission. Despite these variations, the overall accuracy remains sufficient for real-time power monitoring and operational decision-making.

The ACS712-05A current sensor also performed well, although small deviations were observed in certain measurements. Such deviations may stem from the sensor's sensitivity to electromagnetic noise and temperature fluctuations, which are common issues in outdoor agricultural environments. Similar studies in IoT-based solar power monitoring have reported comparable challenges, suggesting that additional filtering techniques or sensor calibration methods could further improve accuracy. Despite these limitations, the results indicate that sensor performance remains adequate for greenhouse monitoring, especially in small-scale operations. Another important aspect is the system's ability to calculate energy consumption and estimate electricity costs. This feature provides farmers with actionable insights into energy use, which is particularly valuable in managing operational budgets. In conventional greenhouse systems, energy costs represent a significant portion of production expenses, and the ability to monitor and optimize consumption directly supports cost efficiency.

The integration of solar panels as the main power source represents a significant contribution to sustainability in smart farming. Indonesia, located near the equator, benefits from high solar radiation levels averaging 4.5 kWh/m²/day, making solar photovoltaic systems an attractive and practical solution. By coupling solar power with IoT-based monitoring, this research addresses both the need for renewable energy adoption and the requirement for efficient energy management in agricultural practices. However, several challenges remain. The system currently depends on internet connectivity, which can be unreliable in certain rural areas. Occasional data delays of up to one hour were observed, indicating that optimization of data transmission protocols or local data caching may be required to improve responsiveness. Furthermore, the prototype relies on the free version of Firebase, which imposes limitations on capacity and scalability. For large-scale applications, upgrading to premium cloud services or adopting hybrid data storage solutions could provide more robust performance. Compared with previous research, this study offers a more comprehensive integration by not only monitoring power generation but also linking the data with cost estimation features in a user-friendly Android application. Earlier works have often relied on web platforms or third-party applications, which may reduce usability. The proposed system thus advances the state of smart farming by improving accessibility, reliability, and decision-making support.

The load calculations confirm that the control and monitoring circuit can safely support the operational requirements of the water pump. Current and voltage readings remained within the permissible range of the sensor and microcontroller system during testing.

Compared with prior IoT-based agricultural monitoring systems, the proposed framework presents several distinct advantages. Previous studies predominantly focused on environmental parameter measurements, such as temperature, humidity, soil moisture, and irrigation scheduling, overlooking the monitoring of electrical consumption. For example, the systems developed in [7, 9] highlight the importance of IoT for irrigation control and big-data handling, but do not incorporate real-time tracking of electrical loads. Similarly, greenhouse control models using fuzzy logic, such as those proposed in [8], emphasize microclimate regulation without addressing transparency in energy use. In contrast, this study provides a low-cost integrated solution that not only monitors voltage and current but also estimates energy consumption and operational costs, offering a more comprehensive approach to greenhouse sustainability.

The system exhibited occasional data delays of up to one hour, primarily caused by unstable Wi-Fi connectivity and the limited bandwidth of the Firebase free-tier database. Environmental interference, such as electromagnetic noise from motors and temperature variations, also contributed to minor deviations in sensor readings. Future improvements could include local buffering at the NodeMCU, noise-filtering circuits, and migrating to a dedicated cloud server to reduce latency and improve scalability.

The findings highlight that IoT-based power monitoring systems can significantly improve transparency, efficiency, and sustainability in greenhouse agriculture. By providing real-time data and actionable insights, farmers are empowered to optimize energy consumption, reduce dependence on conventional electricity, and move toward more environmentally sustainable agricultural practices.

IV. CONCLUSIONS

This study designed and implemented an IoT-based electrical power monitoring system for a smart farming greenhouse powered by solar energy. The developed system integrates a NodeMCU ESP8266 with ACS712-05A current and ZMPT101B voltage sensors, with the acquired data transmitted to a Firebase Realtime Database and displayed through an Android-based application. The experimental results showed that the system could operate effectively, with all the application features functioning properly, as verified by black box testing. The voltage sensor demonstrated high accuracy in most tests, with only a minor deviation occurring in one measurement, while the current sensor also provided reliable results despite the small discrepancies observed in a limited number of cases. The findings indicate that the system is capable of delivering accurate real-time monitoring, recording historical consumption data, and estimating electricity costs, which supports efficient energy management in greenhouses. Furthermore, the utilization of solar panels as the main power source reduces the dependence on grid electricity and enhances sustainability in agricultural practices.

Although the system shows promising performance, several limitations must be acknowledged. The monitoring process is heavily dependent on Wi-Fi connectivity, resulting in occasional data delays of up to one hour during periods of weak signal strength. The use of the free-tier Firebase Realtime Database also imposes constraints on data storage capacity and refresh rates, affecting the scalability and responsiveness of the system. Additionally, the ACS712-05A current sensor is sensitive to environmental noise, which may introduce slight measurement deviations under certain conditions. Future improvements may involve implementing local data buffering on the microcontroller, integrating hardware noise filters, and migrating to a higher-capacity cloud service to enhance system performance and robustness.

IoT-based monitoring systems play an important role in improving efficiency, transparency, and sustainability in smart farming. However, further work is still needed to optimize data synchronization, expand accessibility across platforms, and enhance cloud service capacity to overcome the limitations identified in this prototype.

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