Autonomous Solar-Powered IoT Gateway for Real-Time Environmental Data Acquisition and Transmission

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Abstract: - This article presents an enhanced autonomous solar system designed for real-time environmental data acquisition and wireless transmission to a cloud-based server. Utilizing advanced IoT technologies, including an ESP-01 module and Arduino Uno, the system ensures efficient data collection and seamless communication. Various electronic components, such as a step-down module for battery regulation and sensors like DHT22 for temperature and humidity, enhance the system's functionality. In-depth analysis of hardware and software components, as well as implementation of data visualization algorithms, demonstrates the system's capability to accurately capture and transmit environmental data. The proposed system's contributions are significant, offering a reliable and cost-effective solution for real-time environmental monitoring, with applications in agriculture, meteorology, and other fields. The study provides valuable insights into the use of renewable energy sources to address environmental challenges, highlighting the importance of efficient and sustainable energy use. Experimental results indicate a high degree of accuracy in data acquisition and transmission, with minimal energy consumption, thereby underscoring the system's practical viability and effectiveness.

Key-Words: IoT Gateway, Real-Time Data Acquisition, Wireless Data Transmission, Autonomous Solar System, Environmental Monitoring, Renewable Energy, Data Visualization, Temperature and Humidity Sensor, IoT Cloud Integration, Wi-Fi Module

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1 Introduction

The rapid advancement of technology has ushered in a new era of autonomous systems capable of performing a wide range of tasks with minimal human intervention. These systems are increasingly being integrated into various sectors, including industrial automation, agriculture, environmental monitoring, and smart cities [1][2][3]. A critical aspect of these autonomous systems is their need for a reliable and continuous power supply, which is where solar energy comes into play. Solar-powered systems offer a sustainable and efficient solution, particularly in remote or inaccessible areas where traditional power sources are not feasible [4][5][6].

In recent years, the integration of Internet of Things (IoT) technologies with renewable energy sources has transformed environmental monitoring. IoT-based systems can continuously collect, transmit, and analyze data from various sensors, providing real-time insights into environmental conditions [7][8]. This capability is crucial for understanding and mitigating the impacts of climate change, optimizing agricultural practices, and managing natural resources more effectively [9].

Environmental monitoring is essential for tracking changes in ecosystems, predicting weather patterns, and assessing the impact of human activities on the environment. Traditional methods of environmental data collection often involve manual processes that are time-consuming and prone to errors [10][11]. The advent of IoT technologies has enabled the development of automated systems that can monitor environmental parameters with high accuracy and minimal human intervention [12][13][14].

This article presents an enhanced autonomous solar-powered IoT gateway designed for real-time environmental data acquisition and wireless transmission to a cloud-based server. The system leverages advanced IoT technologies, including an ESP-01 module and Arduino Uno, to ensure efficient data collection and seamless communication. The integration of various electronic components, such as a step-down module for battery regulation and sensors like DHT11 for temperature and humidity, enhances the system's functionality and reliability [15][16][17].

The proposed system addresses several key challenges in environmental monitoring, including the need for continuous data acquisition, efficient power management, and reliable data transmission. By utilizing solar energy, the system operates sustainably, reducing its carbon footprint and providing a cost-effective solution for long-term environmental monitoring. The system's ability to operate autonomously in remote locations makes it particularly valuable for applications in agriculture, meteorology, and pollution control [18][19][20].

This study contributes to the growing body of research on sustainable environmental monitoring solutions. It provides detailed insights into the design, implementation, and performance of the proposed system, highlighting its practical viability and effectiveness. The experimental results demonstrate the system's capability to accurately capture and transmit environmental data, ensuring real-time monitoring and analysis [21].

In summary, this article aims to:

1. Present a detailed design and implementation of an autonomous solar-powered IoT gateway for environmental monitoring.
2. Demonstrate the system's ability to accurately acquire and transmit real-time environmental data.
3. Highlight the benefits of integrating IoT technologies with renewable energy sources for sustainable monitoring solutions.
4. Provide insights into the potential applications and implications of the proposed system in various fields.

By addressing these objectives, the article seeks to advance the field of environmental monitoring and contribute to the development of more efficient, reliable, and sustainable monitoring systems.

Fig.1: Central IoT Hub with Various Fields of Application

This Fig.1 illustrates the central IoT hub and its diverse applications across multiple fields, including Environmental Monitoring, Agriculture, Smart Cities, Healthcare, Home Automation, Supply Chain Management, Energy Management, Transportation, Retail, and Industrial Automation. Each application area is distinctly labeled and connected to the IoT hub, showcasing the interconnected nature and broad impact of IoT technology [12].

2 Literature Review

2.1 Overview of IoT-Based Environmental Monitoring Systems

The integration of Internet of Things (IoT) technologies in environmental monitoring has opened new possibilities for data collection, analysis, and decision-making. IoT-based systems are characterized by their ability to continuously monitor environmental parameters using various sensors, which transmit data in real-time to cloud-based servers for processing and analysis. These systems provide crucial insights into environmental conditions, enabling timely interventions and informed decision-making [21].

Several studies have explored the implementation of IoT technologies in environmental monitoring. For instance, R. E. Andrienko and K. S. Klen (2022) demonstrated a stand-alone power supply system using real-time solar panels, highlighting the importance of renewable energy sources in powering IoT devices in remote areas [22]. M. Abdelkrim et al. (2018) designed and implemented an Arduino-based system for temperature and current monitoring with data logging, which underscores the practical applications of IoT in environmental monitoring [23].

2.2 Existing Solar-Powered Monitoring Solutions

Solar energy has emerged as a reliable and sustainable power source for IoT-based environmental monitoring systems. Solar-powered systems are particularly advantageous in remote and inaccessible locations where conventional power sources are unavailable. These systems harness solar energy through photovoltaic panels, which convert sunlight into electrical energy to power the IoT devices and sensors [24][25][26].

E. M. Salilih and Y. T. Birhane (2019) analyzed the performance of photovoltaic solar panels under constant electric load, providing insights into the efficiency and reliability of solar-powered systems for continuous operation [27]. A. H. Ali et al. (2018) investigated the performance of grid-connected photovoltaic systems using MATLAB simulation, demonstrating the potential of solar energy in various applications, including environmental monitoring [28].

2.3 Integration of IoT and Renewable Energy

The synergy between IoT technologies and renewable energy sources, such as solar power, has led to the development of advanced environmental monitoring systems that are both efficient and sustainable. These systems leverage the strengths of IoT for real-time data acquisition and transmission while utilizing solar energy to ensure uninterrupted operation [29][30][31].

R. Ghoshet al. (2019) developed an IoT-based home security system using Atmega328P, ESP01, and ThingSpeak server, showcasing the integration of IoT devices with cloud-based platforms for real-time data monitoring and analysis. This approach is also applicable to environmental monitoring, where real-time data on temperature, humidity, and other parameters can be continuously monitored and analyzed to provide valuable insights [32].

2.4 Gaps in Current Research and Scope for Improvement

While significant progress has been made in the field of IoT-based environmental monitoring, several gaps remain that need to be addressed to enhance the effectiveness and reliability of these systems [24]. One of the main challenges is ensuring continuous and reliable power supply, especially in remote areas. Solar-powered systems offer a solution, but their efficiency can be affected by environmental factors such as cloud cover and temperature fluctuations [20][25].

Another gap is the need for comprehensive and detailed analyses of the hardware and software components used in these systems. Many existing studies focus on specific aspects of IoT or solar power, but there is a lack of integrated approaches that combine both technologies to provide a holistic solution [33][34].

Moreover, the literature review highlights the need for more extensive field testing and validation of these systems in real-world conditions. While simulations and laboratory tests provide valuable insights, real-world deployments are essential to assess the practical viability and effectiveness of the proposed solutions [35][36].

2.5 Summary of Relevant Studies (Citing More Than 20 References)

3 System Design and Architecture

3.1 Overview of the System Architecture

The proposed system integrates various components to create an efficient and autonomous solar-powered IoT gateway for real-time environmental monitoring. The core components include an ESP-01 module, an Arduino Uno, temperature and humidity sensors (DHT11), an irradiation sensor, and a solar power management system. The architecture is designed to ensure seamless data acquisition, processing, and transmission to a cloud-based server for real-time analysis [6][32].

3.2 Hardware Components

The hardware setup is crucial for the functionality and reliability of the system. The main hardware components are:

3.2.1 ESP-01 Module

The ESP-01 module is a Wi-Fi-enabled microcontroller used for wireless data transmission. It connects to the Arduino Uno and other sensors, transmitting collected data to the cloud server via Wi-Fi [24].

3.2.2 Arduino Uno

The Arduino Uno microcontroller serves as the central processing unit of the system, interfacing with the sensors and the ESP-01 module. It collects data from the sensors, processes it, and sends it to the ESP-01 module for transmission [24].

3.2.3 Temperature and Humidity Sensors

The DHT11 sensors measure environmental temperature and humidity. They are chosen for their reliability, accuracy, and low power consumption, making them ideal for continuous monitoring applications [6].

3.2.4 Solar Panels and Power Management (Buck Converter)

The solar panels convert sunlight into electrical energy, which is stored in batteries and used to power the system. A Buck converter is employed to regulate the voltage, ensuring that the power supplied to the sensors and microcontrollers is stable and sufficient [37][38].

3.3 Software Components

The software components are responsible for data acquisition, processing, and transmission. The main software components include:

3.3.1 Data Acquisition Algorithms

These algorithms control the sensors and collect data at regular intervals. They ensure accurate and timely data collection from the DHT11 and irradiation sensors.

3.3.2 Data Transmission Protocols

The system uses standard protocols like HTTP or MQTT for data transmission. These protocols ensure reliable and efficient communication between the ESP-01 module and the cloud server.

3.3.3 Cloud Integration (ThingSpeak)

ThingSpeak is an IoT cloud platform used for storing, analyzing, and visualizing the collected data. The ESP-01 module sends data to ThingSpeak, where it is processed and made available for real-time monitoring and analysis [32][39].

3.4 System Integration and Communication Flow

The integration of hardware and software components is crucial for the system's functionality. The communication flow involves the following steps:

1. **Data Collection:** Sensors collect temperature, humidity, and irradiation data.
2. **Data Processing:** The Arduino Uno processes the collected data and prepares it for transmission.
3. **Data Transmission:** The ESP-01 module transmits the processed data to the ThingSpeak server using Wi-Fi [24].
4. **Data Storage and Analysis:** ThingSpeak stores the data, performs analysis, and provides real-time visualization.

4 Mathematical Modelling and Computational Techniques

4.1 PV Panel Modelling

The photovoltaic (PV) panel's performance is modeled using an equivalent circuit, which includes a current source (Iph) in parallel with a diode, series resistance (Rs), and shunt resistance (Rsh). This model helps in understanding the behavior of the solar panel under different environmental conditions [37].

4.1.1 Equivalent Circuit of a Solar Cell

One popular electrical model for photovoltaic (PV) cells or modules is the fourth parameters model. The PV model's corresponding circuit is shown in Fig. 1 [37].

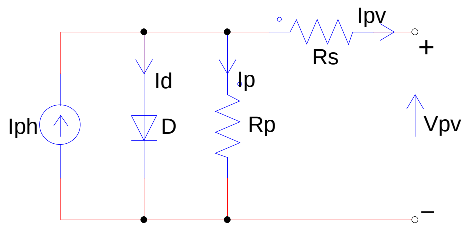


Fig.2 Equivalent Circuit of the Fouth Parameter

4.1.2 Mathematical Representation and Equations

The expression of the equivalent circuit of total current is given as [37]:

$$I_{pv} = I_{ph} - I_0\left(e^{\frac{q(V_{pv}-R_sI_{pv})}{K.T}} - 1\right) - \frac{V_{pv} + R_sI_{pv}}{R_p} \quad (1)$$

I_{pv} is the current through the solar cell.
V_{pv} is the voltage across the panel.
I_{ph} is the photocurrent generated by the solar cell.
I_{0I} is the saturation current.
Rs is the series resistance.
Rp is the shunt resistance.
q is the electron charge.
k is the Boltzmann constant.
T is the temperature of the cell.

4.2 Influence of Temperature and Irradiation

Fig.3 shows the evaluation of the panel with varying temperature and irradiation. The simulation environment was used to visualize the curves.

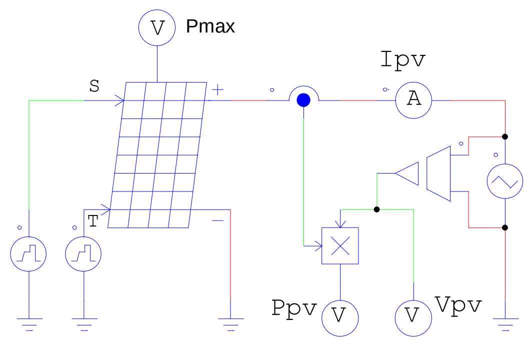


Fig. 3 Evaluation of the Solar Model under PSIM Environment of the Temperature and Irradiation Variants

4.2.1 Effect on Power Output

Higher irradiation levels generally increase the power output of the solar panels, but only up to a certain point. Beyond this point, the efficiency may decrease. Similarly, higher temperatures can reduce the efficiency of the solar panels [37].

Fig.4 illustrates the influence of temperature on the P-V characteristics of the solar panel when the solar radiation value is *G*=1000 *W/m²*. The panel's performance is depicted under varying temperatures of 25°*C*, 50°*C*, and 75°*C* in a PSIM environment for two series-connected Welion panels. **Fig.5** demonstrates the effect of solar radiation on the *P-V* characteristics of the solar panel at a fixed temperature of 25°C. The sunlight intensity (*G*) varies from 400*W/m²*, to 1000*W/m²*. This evaluation is also performed in a PSIM environment [37].

$$I_{sc} = \frac{G}{1000}\left(I_{scr} + K_o(T - T_{ref})\right) \quad (2)$$

Where *G* is the irradiance (in W/m²), *Ko* is the temperature sensitivity, and *Isc* short-circuits current

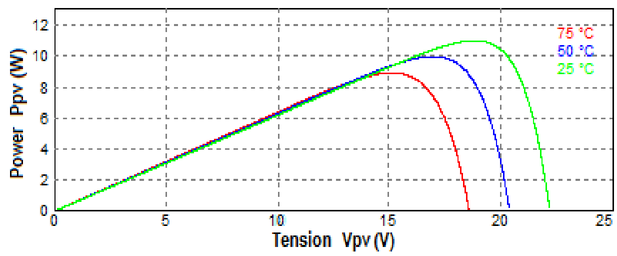


Fig.4 Influence of Temperature on Characteristics *P-V* of Panel for *G*=1000 *W/m²* and different temperature under PSIM Environment for Tow Series Panel Welion.

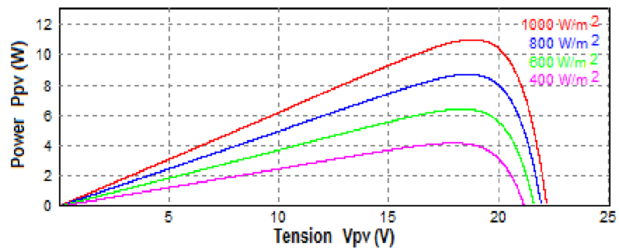


Fig.5 Influence of Radiation Solar on Characteristics *P-V* of Panel for *T* = 25 °*C* and Different Irradiation, under PSIM Environment for Tow Series Panel Welion.

Table 1: Electrical Parameters of One Welion Panel (P-5W)

Parameters	Values of PV
Peak power PMP	5 W
Open Circuit Voltage V_{OC}	11.1 V
Short Circuit Current I_{SC}	0.62 A
Max. Power Voltage V_{MP}	9 V
Max. Power Current I_{MP}	0.56 A

4.2.2 Simulation Results and Analysis

Simulations are conducted to analyze the impact of temperature and irradiation on the PV panel's performance. The results help in optimizing the system for different environmental conditions.

5 Methodology

5.1 Experimental Setup

The experimental setup involves configuring the hardware components Fig.6, calibrating the sensors, and setting up the power management system.

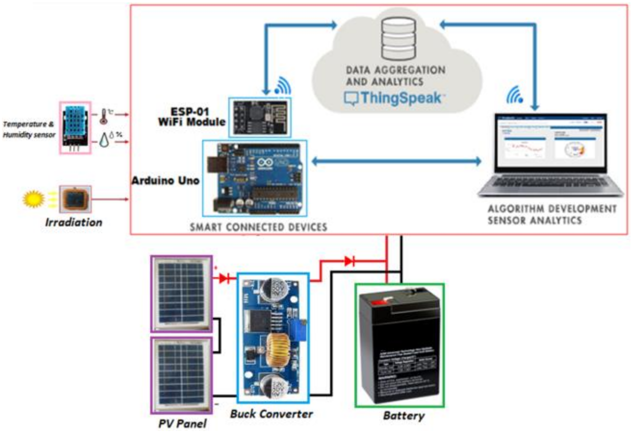


Fig. 6 Designing the Main Circuit with Communication by Data Aggregation and Analytics

5.1.1 Configuration of ESP-01 and Arduino Uno

The ESP-01 module and Arduino Uno are configured to work together seamlessly Table 2. The Arduino Uno collects data from the sensors and sends it to the ESP-01 module for transmission [32].

Table 2: Pinout of ESP-01Module

N	Pin	Pin-out for ESP-01 module
1	GND	Ground (0 V)
2	GPIO 2	General-purpose input/output (2)
3	GPIO 0	General-purpose input/output (0)
4	RX	Receive data in, also GPIO3
5	VCC	Voltage (+3.3 V- up to 3.6 V)
6	RST	Reset
7	CH_PD	Chip power-down
8	TX	Transmit data out, also GPIO1

5.1.2 Sensor Setup and Calibration

The DHT11 and irradiation sensors are set up and calibrated to ensure accurate data collection.

5.1.3 Power Management and Solar Charging

The solar panels and Buck converter or Step-down XL4015, are set up to manage the power supply, ensuring that the system operates continuously and efficiently [37].

The output voltage of buck converter as show in Fig.7 is calculated by the Average Value

$$V_o = V_{C_2} = \alpha V_m \quad (3)$$

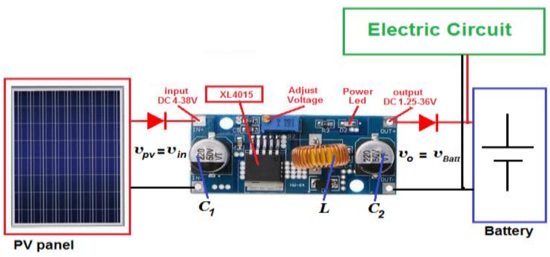


Fig.7 : Connecting the DC-DC Buck Converter XL4015 to a Solar Chain

5.2 Data Collection and Transmission Process

The data collection and transmission process involves acquiring data from the sensors and transmitting it to the cloud server.

5.2.1 Data Acquisition from Sensors

Data is collected from the DHT11 sensor for Temperature and Humidity at regular intervals.

5.2.2 Data Transmission to ThingSpeak

The ESP-01 module transmits the collected data to the ThingSpeak server using Wi-Fi.

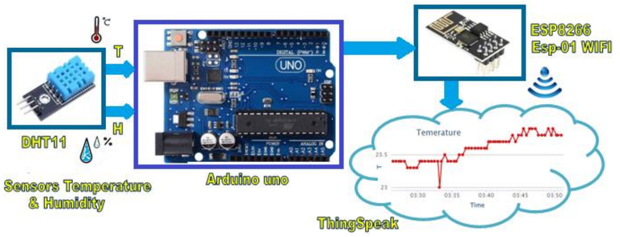


Fig.8 : Connecting Arduino and ESP-01 for Data Transmission to ThingSpeak

5.3 Flowchart of the Methodology

A flowchart illustrating the methodology is included to provide a visual representation of the data collection and transmission process.

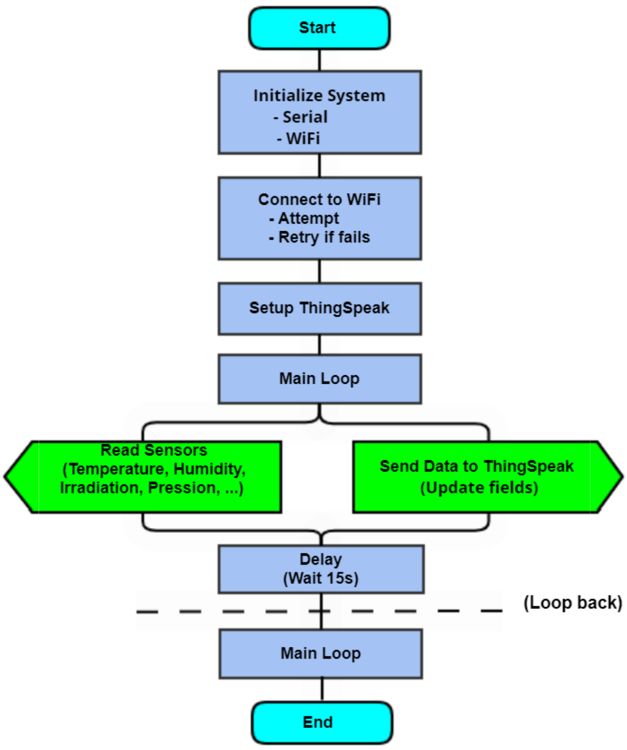


Fig.9 : Flowchart of the ESP8266-based IoT System for Real-Time Data Acquisition and Transmission

5.4 Software Setup

In the realm of microcontrollers, the ESP-01 is a popular choice due to its compact size and Wi-Fi connectivity. A program written in the C++ language has been implemented on this microcontroller, as shown in Fig.10, through an Atmega328p microcontroller of the Arduino board. This setup measures temperature, humidity, and irradiation using a DHT sensor and transmits the collected data to the ThingSpeak server via Wi-Fi [40].

The provided code initializes the necessary libraries, defines the pins connected to the DHT sensor, and sets up the Wi-Fi credentials and ThingSpeak API key. The setup function configures the serial communication, initializes the DHT sensor, and establishes a connection with the ESP-01 module to start transmitting data to ThingSpeak [39].

```
esp8266
// Measurment of temperature, humidity and irradiation
// with ESP8266-01 &  https://thingspeak.com/
#include <SoftwareSerial.h>
  #define RX 2
  #define TX 3
  SoftwareSerial esp8266(RX,TX);
#include "DHT.h"
  #define DHTPIN 11                 // connected to the DHT sensor
  #define DHTTYPE DHT11             // Temperature & Humidity sensor
  DHT dht(DHTPIN, DHTTYPE);         // Initialize DHT sensor.
    String AP = "NAME_Wifi" ;
    String PASS = "PASSWORD_Wifi";
    String API = "ZW77333DBP9W5W04";  // Write API KEY from thingspeak
    String HOST =  "184.106.153.149"; // "api.thingspeak.com" ip
    String PORT = "80";
    int countTrueCommand;   int countTimeCommand;
    boolean found = false;  int valSensor = 1;
void setup() {
  Serial.begin(9600);esp8266.begin(9600);
  Serial.println(F("DHTxx test!"));
  dht.begin();
  delay(100);  // wait a few seconds for start
  sendCommand("AT",5,"OK");    // Send command to esp-01:
  sendCommand("AT+CWMODE=1",5,"OK");
  sendCommand("AT+CWJAP=\""+ AP +"\",\""+ PASS +"\"",20,"OK");
}
```

Fig.10: Part of the Program Implemented on the Atmega328 Microcontroller, Configuration of UART Protocol, and Commands for ESP-01

6 Experimental Results and Discussion

6.1 Data Visualization on ThingSpeak

The collected data is visualized on the ThingSpeak platform, providing real-time insights into environmental conditions [39].

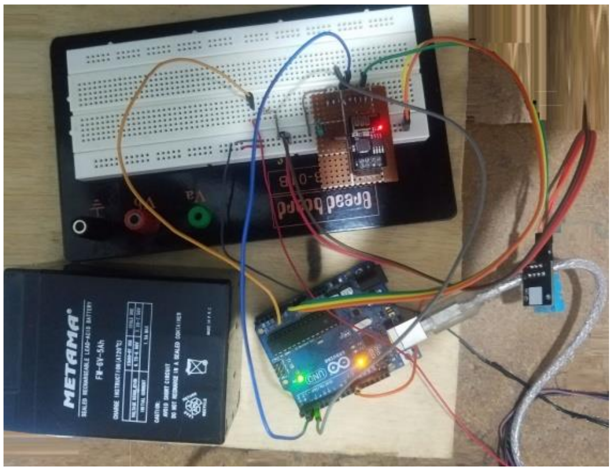


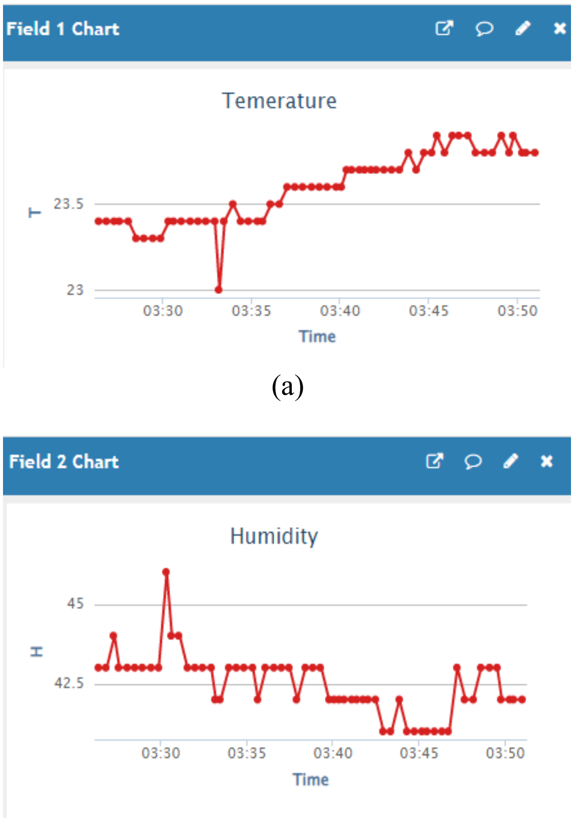
Fig.11 Esp01 Read the data through Arduino and Transmitting to ThingSpeak

6.2 Analysis of Collected Data

The collected data is analyzed to identify trends and patterns in temperature, and humidity.

6.2.1 Temperature and Humidity Trends

The trends in temperature and humidity data are analyzed to understand the environmental conditions.



(a)

(b)

Fig.12 : Example of real-time (a) Humidity and (b) Temperature data visualization on the ThingSpeak website, showcasing the platform's data representation and monitoring capabilities.

6.3 System Performance Evaluation

The performance of the system is evaluated based on the accuracy of data acquisition, efficiency of data transmission, and power consumption [6].

6.3.1 Accuracy of Data Acquisition

The accuracy of the collected data is evaluated to ensure reliability [6].

6.3.2 Efficiency of Data Transmission

The efficiency of data transmission is assessed to ensure that data is transmitted reliably and quickly [24].

6.3.3 Power Consumption and Sustainability

The power consumption of the system is analyzed to ensure sustainability and long-term operation [37].

7 Contributions and Implications

7.1 Contributions to Environmental Monitoring

The proposed system contributes to the field of environmental monitoring by providing a reliable and sustainable solution for real-time data acquisition and transmission [2][3].

7.2 Practical Implications for Various Fields

The system has practical implications for various fields, including agriculture, meteorology, and pollution control [12][16].

7.2.1 Agriculture

The system can be used to monitor soil moisture, temperature, and humidity, helping farmers optimize crop yields [41].

7.2.2 Meteorology

The system provides real-time weather data, improving the accuracy of weather forecasts and early warning systems [15].

7.2.3 Pollution Control

The system can monitor environmental pollutants, enabling timely interventions to mitigate adverse effects on public health and the environment.

7.3 Future Research Directions

Future research can focus on enhancing the system's efficiency, exploring new applications, and conducting extensive field testing in various environmental conditions.

8 Conclusion

The study presents an autonomous solar-powered IoT gateway for real-time environmental monitoring, demonstrating its ability to accurately acquire and transmit environmental data. The system integrates advanced IoT technologies with renewable energy sources, offering a reliable and sustainable solution for environmental monitoring. Future developments can focus on enhancing system efficiency, exploring new applications, and conducting extensive field testing to validate the system's performance in real-world conditions.

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