IoT Gateway Powered by Renewable Energy for Cloud Connectivity and Real-Time Environmental Monitoring

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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 DHT11 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 integrated into various sectors, including industrial automation, agriculture, environmental monitoring, and smart cities. For instance, Sunny et al. [1] explored the use of low-cost IoT sensor systems for harsh environmental monitoring, while Ullo and Sinha [2] highlighted advancements in smart environmental monitoring using IoT and sensor technologies. Additionally, Zhang et al. investigated the deep integration of artificial intelligence into environmental monitoring systems to enhance real-time data collection and decision-making [3].

A critical aspect of these autonomous systems is the need for a reliable and continuous power supply, where solar energy plays a key role. Solar-powered systems offer a sustainable and efficient solution, especially in remote or inaccessible areas where traditional power sources are not feasible [4], [5], [6]. For example, Afreen et al. [4] proposed sustainable and green IoT solutions for environmental monitoring, and Muñiz et al. explored the integration of solar-powered smart buildings with IoT for sustainability, providing a comprehensive energy management system [5].

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]. Mukhopadhyay et al. [8], showing their potential to improve environmental data accuracy. 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 capable of monitoring environmental parameters with high accuracy and minimal human intervention [12][13][14].

Subeesh and Mehta discussed the application of IoT in precision agriculture, while Nižetić et al. [13] analyzed the challenges and opportunities of IoT in promoting sustainability.

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, such as the 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].

Kishorebabu and Sravanthi demonstrated the practical applications of such technologies in real-time environmental monitoring, while Pisanu et al. developed a low-cost platform for real-time greenhouse monitoring, emphasizing agriculture 4.0 solutions [16].

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 [18]. This is particularly valuable for applications in agriculture, meteorology, and pollution control, as outlined by Rabaia et al. [19] and Al-Shahri et al. [20], who studied the environmental impacts of solar energy systems and their optimization.

This study contributes to the growing body of research on sustainable environmental monitoring solutions by providing detailed insights into the design, implementation, and performance of the proposed system, highlighting its practical viability and effectiveness. Experimental results from previous works, such as those by Fu et al. [21], demonstrate the capability of solar-powered IoT systems to capture and transmit environmental data accurately, ensuring real-time monitoring and analysis [21].

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 System Design and Architecture

2.1 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][21][22][23].

2.2 Hardware Components

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

2.2.1 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].

2.2.2 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 [25].

2.2.3 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].

2.2.4 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 [26][27].

2.3 Software Components

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

2.3.1 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.

2.3.2 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. This enables the seamless transfer of sensor data from the connected devices to the ThingSpeak platform, where it can be processed and analyzed for various applications. [28][29][30].

2.3.3 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 [23][31].

2.4 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:

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

3 Mathematical Modelling and Computational Techniques

3.1 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[32].

3.1.1 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 [26].

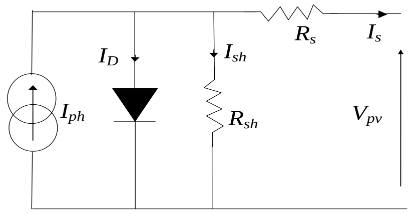


Fig.2: Equivalent Circuit of the Fouth Parameter

3.1.2 Mathematical Representation and Equations

The expression of the equivalent circuit of total current is given as [26]:

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

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.

3.2 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.

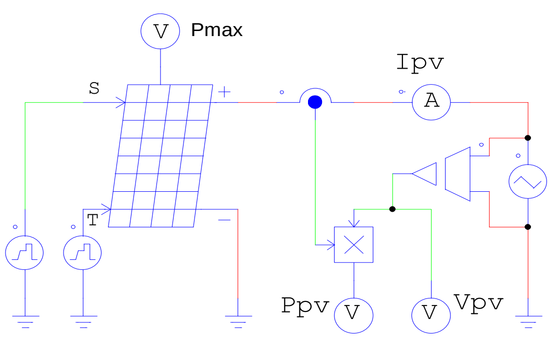


Fig.3: Evaluation of the Solar Model under PSIM Environment of the Temperature and Irradiation Variants

3.2.1 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 [26].

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 [26][33].

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

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

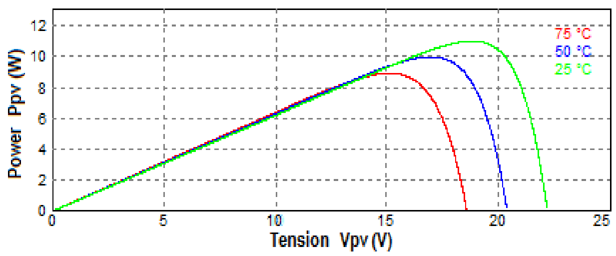


Fig.4: Influence of Temperature on Characteristics *P-V* of Panel for *G*=1000 *W/m²* and different temperature under PSIM Environment for Tow Series Panel Welion.

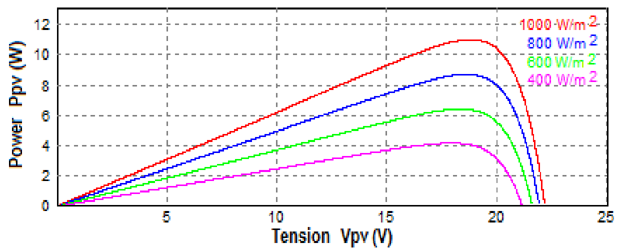


Fig.5: Influence of Radiation Solar on Characteristics *P-V* of Panel for *T* = 25 °*C* and Different Irradiation, under PSIM Environment for Tow Series Panel Welion.

Table 1: Electrical Parameters of One Welion Panel

Parameters (P-5W)	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

3.2.2 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.

4 Methodology

4.1 Experimental Setup

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

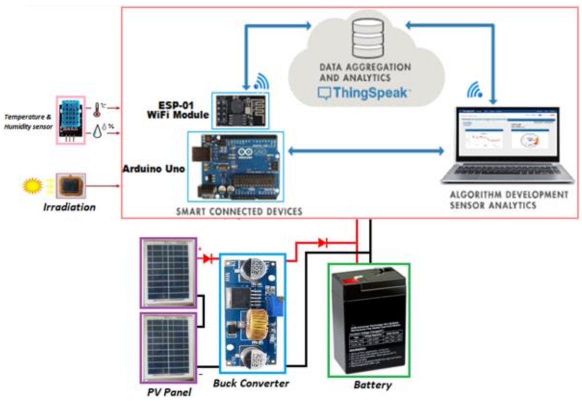


Fig.6: Experimental Setup with Main Circuit and Communication via Data Aggregation and Analytics

4.1.1 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 [23][34].

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

The ESP-01 is a compact, low-cost Wi-Fi module by Espressif Systems, designed for easy integration with Arduino devices. It utilizes the ESP8266, a widely used SoC with built-in CPU, Wi-Fi baseband processor, and MAC, offering cost-effective Wi-Fi connectivity. The module is small and simple to use, even for beginners, with AT commands similar to those of GSM modules. The ESP-01 features essential components like the ESP8266 chip, a 26 MHz crystal oscillator, LEDs, and reset buttons [34]. It operates on 3.3V DC and supports WEP/WPA/WPA2 authentication for secure connections. The module is commonly used in wireless sensor networks (WSNs) and applications like smart homes and agriculture. Programming it with Arduino involves using AT commands and connecting the module via TXD and RXD pins, with a USB to UART bridge controller facilitating the communication [35][36].

4.1.2 Sensor Setup and Calibration

The proposed model uses DHT11 temperature and humidity sensors. The DHT11 provides results in both digital and analog formats. The DHT11 and irradiation sensors are set up and calibrated to ensure accurate data collection [37][38].

4.1.3 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 [26].

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

$$V_o = V_{C_2} = \alpha V_m \tag{3}$$

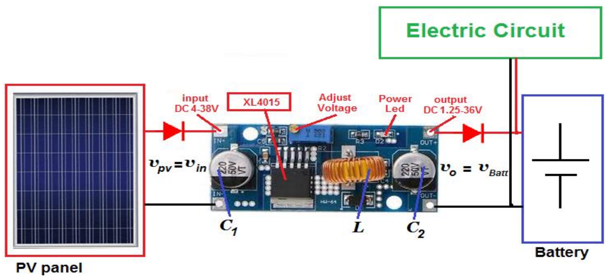


Fig.7: DC-DC Buck Converter Connected to the XL4015 and Solar Chain

4.2 Data Collection and Transmission Process

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

4.2.1 Data Acquisition from Sensors

The proposed model uses DHT11 temperature and humidity sensors. The DHT11 provides results in both digital and analog formats. Data is collected from the DHT11 sensor for Temperature and Humidity at regular intervals [37][38].

4.2.2 Data Transmission to ThingSpeak

In the ESP-01 module, data transmission to ThingSpeak is achieved via HTTP GET requests, facilitating seamless data posting or retrieval. This process involves pushing data to the ThingSpeak server through these requests. The module establishes a connection with a Wi-Fi router, enabling it to send and receive HTTP requests over the internet. The URL used in this transmission contains [39][40]:

- api_key: The channel's write API key in the format provided.
- fieldX: The fields where the measurement values will be stored.

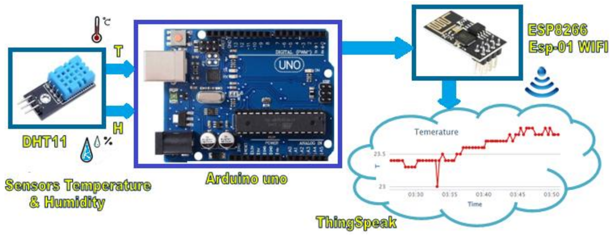


Fig.8: Connecting of Arduino and ESP-01 for Data Transmission to ThingSpeak

4.3 Flowchart of the Methodology

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

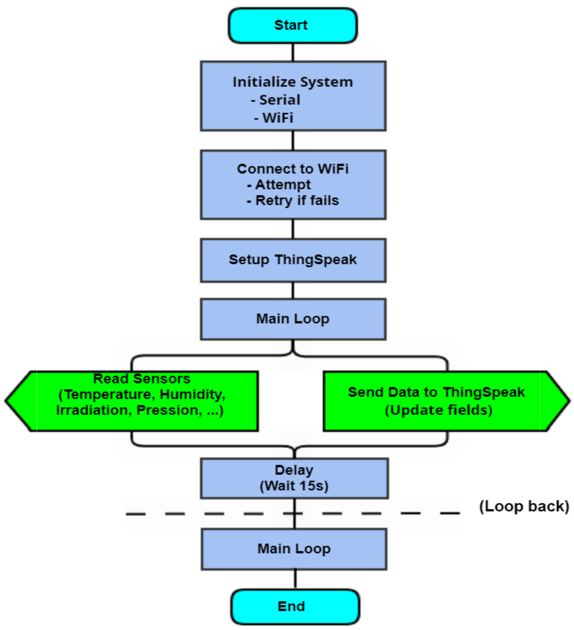


Fig.9: Flowchart of the ESP8266-based IoT System for Real-Time Data Acquisition and Transmission

4.4 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 [41][42].

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 [28][31].

```
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

5 Experimental Results and Discussion

5.1 Data Visualization on ThingSpeak

The collected data is visualized on the ThingSpeak platform, providing real-time insights into environmental conditions [31].

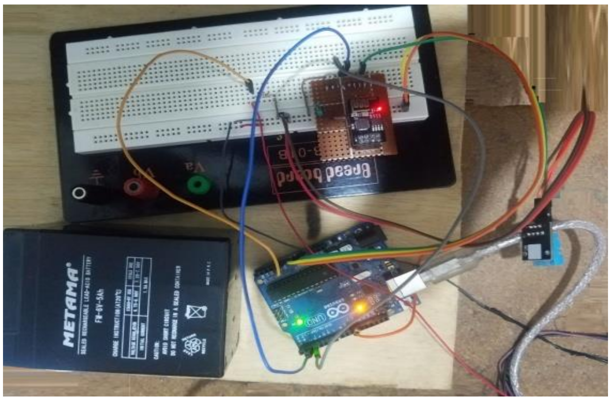


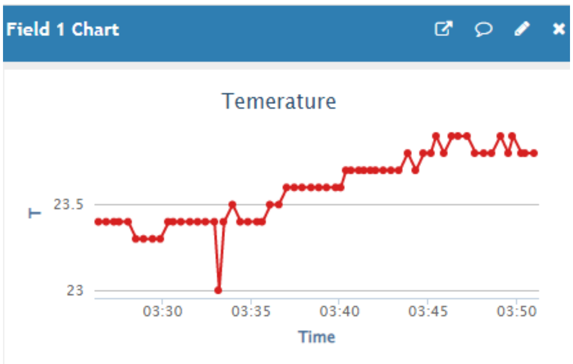
Fig.11: Data Transmitting to ThingSpeak through Esp01 and Arduino

5.2 Analysis of Collected Data

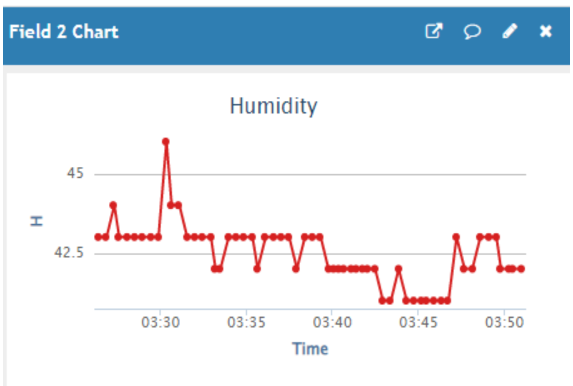
The collected data is analyzed to identify trends and patterns in temperature, and humidity. This analysis enables the optimization of environmental control systems and enhances the performance of IoT applications that rely on accurate data collection [43].

5.2.1 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) Humidityand (b) Temperaturedata visualization on the ThingSpeak website, showcasing the platform's data representation and monitoring capabilities.

Fig.13 shows the solar panel voltage (Vpv) fluctuates slightly around 19.68V to 20.26V. On the other hand, the output voltage (V_o) remains constant at 7.23V.

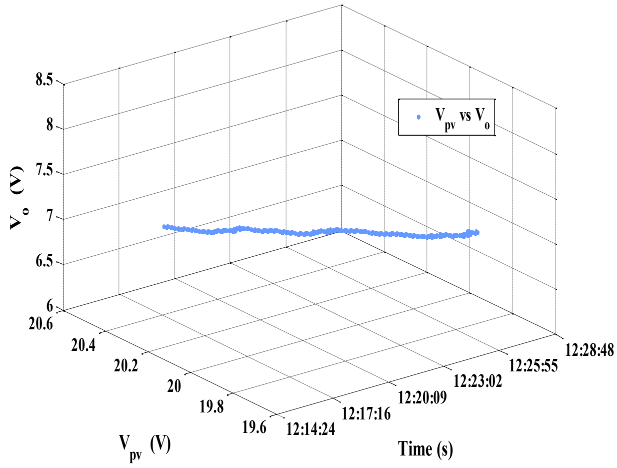


Fig.13: Voltages responses of the photovoltaic panel and DC /DC converter over time presented in 3D.

The system is maintaining a regulated and constant output voltage (V_o) to supply power to the IoT gateway and sensors. The fluctuations in solar panel voltage reflect varying environmental conditions like sunlight intensity. However, the voltage regulation mechanism ensures that the IoT system receives stable voltage, which is critical for reliable operation.

Fig.14 shows the power generated by the solar panels (P_{pv}) ranges between 7.67W and 8.54W, while the output power (P_o) fluctuates between 4.14W and 4.72W. The system converts approximately 52% to 56% of the solar panel power into usable output power. This indicates that about half of the solar energy is successfully used to power the IoT gateway and sensors. The remaining energy might be lost due to conversion inefficiencies, heat dissipation, or stored in energy storage devices. Despite these losses, the system is delivering a significant amount of power to the IoT devices.

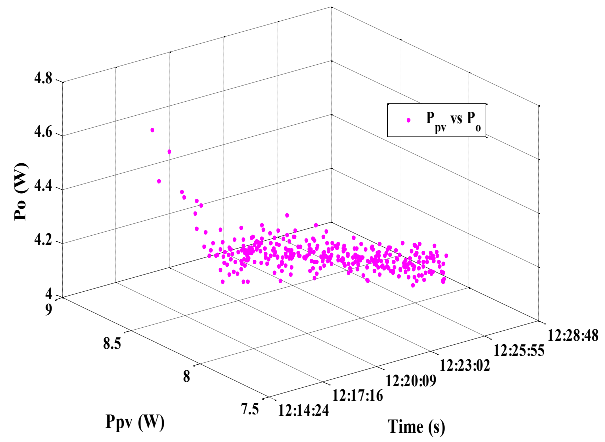


Fig.14: Powers responses of the photovoltaic panel and DC /DC converter over time presented in 3D.

Fig.15 shows the current from of the solar panels (I_{pv}) ranges between 39.2 mA and 42.2 mA, while the output current (I_o) of the converter is significantly higher, ranging from 57.3mA to 65.1 mA. This current (I_o) compared to the input current (I_{pv}) indicates that the system is stepping down the voltage (from around 20V to 7.23V) to meet the voltage requirements of the IoT gateway.

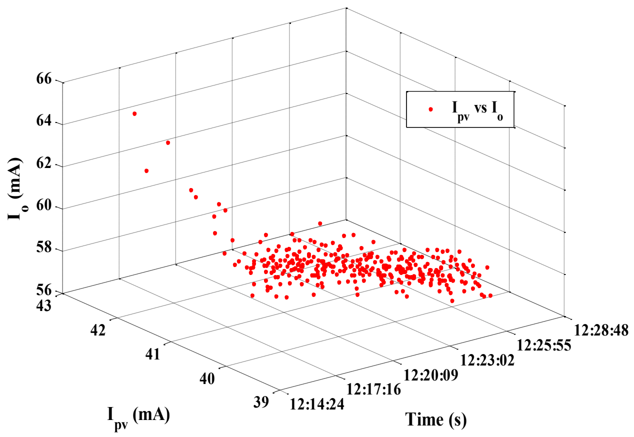


Fig 15: Currents responses of the photovoltaic panel and DC /DC converter over time presented in 3D.

6 Conclusion

This study presents the design and implementation of an autonomous solar-powered IoT gateway for environmental monitoring, emphasizing its efficiency, sustainability, and practical viability. By integrating IoT technologies, such as the Arduino Uno, ESP-01 Wi-Fi module, and environmental sensors like the DHT11, the system effectively captures and transmits real-time environmental data to a cloud-based platform. The solar power system ensures continuous operation, even in remote locations, making it an ideal solution for long-term, sustainable monitoring of environmental parameters.

The proposed system addresses key challenges in environmental monitoring, including efficient power management, reliable data transmission, and accurate, real-time data acquisition. This makes it applicable in various sectors such as agriculture, meteorology, and pollution control. The study contributes to the growing field of IoT-based monitoring systems by providing a scalable, low-cost, and sustainable solution, demonstrating its potential for widespread implementation.

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