

Internet of Things Technology for an Autonomous Photovoltaic Solar Energy System Monitoring

Abdelmalek Mimouni^{1*}, Youssef Chahet², Aumeur El Amrani¹, Mohamed El Amraoui², and Lahcen Bejjit¹

¹MIN research Group, LASMAR, ESTM, Moulay Ismail University of Meknes, Morocco

²LASMAR, Faculty of Sciences, Moulay Ismail University of Meknes, Morocco

Abstract. This work presents a Photovoltaic (PV) monitoring system using the Internet of Things (IoT). It provides a detailed overview of the key steps involved in designing the IoT-based PV monitoring system, examining the specific architectural components, including different system layers, potential software and hardware platforms, and communication network technologies used in the IoT-integrated PV system. Additionally, it discusses the existing challenges and issues of IoT-based PV monitoring systems. Furthermore, it proposes a low-cost monitoring system designed to monitor a PV system consisting of a PV module, a DC-DC boost converter, and a load.

1 Introduction

Solar photovoltaic is widely considered as one of the most important and rapidly growing renewable energy sources, offering the ability to generate clean and sustainable power at various scales from small to large. PV system plays a crucial role in addressing global energy demands, reducing dependence on fossil fuels, and mitigating environmental impact [1]. However, photovoltaic systems exhibit intermittent performance due to their reliance on environmental conditions, while any change in irradiance amounts, fluctuations in temperature, variations in humidity levels, and the accumulation of dust present challenges to reliability and resilience that affect the performance of the system, such as reducing on the overall efficiency and power production [2].

The Internet of Things (IoT) remains one of the revolutionary results of advanced technology. It is a concept that describes the interconnectivity of a wide range of heterogeneous objects to the internet and to each other [3]. The integration of IoT technology with PV systems enables the collection, real-time monitoring, supervision, and analysis of environmental and electrical data. Moreover, PV monitoring systems allow users to monitor energy production and consumption, and weather data in real-time. This capability optimizes energy usage, identifies potential issues, and supports informed decision-making to improve system performance. Additionally, IoT monitoring systems enable remote tracking and control of PV systems. These real-time monitoring systems gather a history of operating parameters, including the voltage, current, and power of the PV systems, as well as locale temperature, humidity, and solar radiation. These historical data can then be used for subsequent analysis and data mining. They also assist in detecting and identifying various faults while predicting PV output power, ensuring optimal performance, improved efficiency, reliability, and reduced maintenance costs [4]. The IoT-based PV monitoring systems offer numerous advantages and benefits. However, several issues and challenges significantly affect the performance of the systems in terms of efficiency, compatibility, scalability, reliability, complexity, security, and privacy [5].

In the literature, several review articles focus on IoT-based PV monitoring systems. The authors in [6] provided an overview of different proposed PV monitoring systems in terms of the design architectures and used communication technologies. Thus, an alternative solution was also proposed that comprehensively addresses the fundamental requirements of a photovoltaic installation monitoring system in a straightforward manner. Ansari et al. in [5] presented an explanation of the monitoring technologies for PV systems, focusing on the categories, specifications, design implementation, software platforms, results, and limitations of various data processing modules and data transmission protocols. The issues and challenges for solar PV monitoring systems were also illustrated. An investigation of the IoT-enabled smart grid systems, including features, architectures, prototypes, applications, advantages, and challenges associated with integrating IoT technology and smart grid presented in [7]. The work reported in [4] provided a comprehensive review of the state-of-the-art application of IoT technology for enhancing the efficiency and management

* Corresponding author: abdel.mimouni@edu.umi.ac.ma

of solar energy utilization. This review examined how IoT is being integrated with solar energy systems to improve various aspects of solar power. The research work presented in [8] provided an overview of techniques, methods, components, and approaches used in intelligent energy management for both independent and grid-connected hybrid renewable energy systems, focusing on IoT in PV power generation.

The rapid growth of IoT technology has spread across a wide range of fields, such as renewable energy. Therefore, IoT-based PV monitoring systems are emerging every day in terms of techniques, methods, components, and approaches. This paper offers a brief review of PV monitoring systems using the Internet of Things, with the following contributions: Examining the specific architectural components, including architecture design, potential software and hardware platforms, and communication network technologies; discussing the existing challenges and issues of IoT-based PV monitoring systems; proposing a low-cost monitoring system to monitor a PV system. Furthermore, an IoT-based PV monitoring system is proposed.

The remainder of this paper is structured as follows: section 2 provides a literature review and discusses the design architectures, hardware and software used, communication protocols, and existing challenges and issues of IoT-based PV monitoring systems; Section 3 presents a proposed low-cost PV monitoring system; Finally, a conclusion is presented in section 4.

2 Literature review and discussion

In recent years, there has been a significant increase in the design and implementation of IoT-based PV monitoring systems, using various materials and methods. The choice of these materials and methods depends on cost, scalability, integration capabilities, security, and the specific requirements of the PV system, which is the subject of monitoring and control. Table 1 presents a brief comparison between some IoT-based PV monitoring systems proposed in the literature in terms of hardware, software, and communication protocols used in these systems.

Table 1. Comparison of some related works

References	Sensors	Data processing and transmission modules	Communication protocols	IoT platforms	Achievements
[9]	ACS712 Hall Effect Current Sensor; Voltage divider circuit	Raspberry Pi + ESP32	MQTT	ThingsBoard	Presented a design and implementation of a low-cost, open-source SCADA system based on the Internet of Things SCADA architecture.
[10]	INA219 sensor; DHT22 sensor; BH1750 sensor	ESP32 board	HTTP	Grafana, Influx DB	Proposed and designed a low-cost and open-source IoT solution that collects intelligently and monitors in real-time the produced power and environmental conditions of solar stations.
[11]	Not mentioned	Moxa UC-2112 PC with Kura installed as IoT Gateway	MQTT and MODBUS protocols	Eclipse Kura, Eclipse Kapua, Grafana platform	implemented and deployed an IoT solution monitoring based entirely on Open-Source software for photovoltaic plants.
[12]	ACS712; Voltage divider circuit; DHT11; BH1750	ESP32 Dev board	Not mentioned	ThingSpeak	Presented an IoT-based intelligent real-time monitoring system for PV power systems, including an MPPT controller.
[13]	ACS712 B25 DHT11 LDR	Arduino Uno R3 + SX1278-LoRa shield + SX1301 LoRaWAN gateway	LoRa	The Things Network and AllThingsTalkMake	Designed and implemented a smart energy meter based on LoRaWAN for monitoring PV systems over IoT.
[14]	Socomec Diris A40 power meter;	ESP8266 board	MQTT and Modbus protocols	ThingSpeak	Proposed an IoT infrastructure solution based on a newly designed low-cost microcontroller-based IoT remote terminal unit to integrate new, old, and conventional sites of existing grids with smart grids.

[15]	DS18B20 temperature sensor; max44009 ambient light sensors; ACS712 current sensor; voltage divider	NodeMCU	MQTT protocol	NET Framework using the C# programming language	Suggested a cloud-based IoT solution for remotely monitoring the amount of soiling on PV panels using an artificial neural network (ANN).
[16]	INA219 voltage and current sensor; TSL2561 luminosity sensor; DHT22 ambient temperature and humidity sensor; Four DS18B20 temperature sensors	Raspberry Pi + ESP8266	MQTT	Node-Red, Mosquitto broker, Grafana, and Influx DB	Introduced a low-cost wireless monitoring system for PV modules that employ NodeMCU boards, Raspberry Pi, and IoT technologies, using free and open-source software packages including MQTT Mosquitto Broker, InfluxDB, Node-RED, and Grafana.
[17]	DHT11 temperature and humidity sensor; ACS712 current sensor; F031-06 voltage sensor; BH1750 digital light sensor	Arduino UNO + ESP8266	Not mentioned	Thingier.io platform	Discussed and designed a real-time monitoring system that uses the Internet of Things technology to monitor the photovoltaic parameters.
[18]	Not mentioned	Raspberry Pi	HTTP, MQTT, and Modbus	Amazon Web Services (AWS)	Introduced an integrated energy management solution for solar-powered smart buildings, combining a multifaceted physical system with advanced IoT and cloud-based control systems.

2.1. Architectures of IoT-based PV monitoring system

Over the past years, the architectures of IoT systems have evolved and changed, with diverse proposed systems exhibiting variations in their layer structures and the specific requirements for each layer [19]. The basic IoT architecture comprises three layers as shown in Fig.1.: (1) the perception (or sensing) layer is the first level of the architecture where data is gathered and acquired from the physical environment through the use of various sensors, microcontrollers, actuators, and other IoT devices; (2) The network (or communication) layer is the middle layer, which handles the transmission and processing of the data gathered by the perception layer. It establishes connections between devices and the network; And (3) the application (or service) layer, which prepares the data received from the network layer and presents them to the end-users through applications, dashboards, or user interfaces [20]. However, with the growth of the proposed IoT systems, the suggested architectures are based on multi-layer such as the four-layer architecture which consists of the following layers: perception, communication, processing, and application [21]. The five-layer architecture includes the middleware and business layers in addition to the 3-layer architecture. The middleware layer is responsible for service management, while the business layer is accountable for managing the overall IoT system including the services and applications [22, 23]. The six-layer architecture is grouped into two groups: The internal layers group consists of four layers: perception, communication, processing, and application layers, which are similar to the 4-layer architecture; and the external layers group consists of two layers: the focus layer, which helps to group the parameters, and the business layer, which helps in creating a strong business network based on the results of the IoT solution [24]. Finally, the seven-layer architecture, which is based on the 4-layer architecture, with the addition of fog computing, service, and session layers [25].

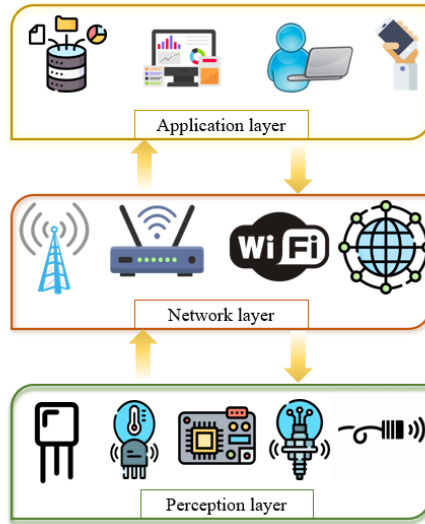


Fig. 1. The basic three-layer IoT system architecture

The IoT-based PV monitoring systems have been widely designed in the literature with a three-layer architecture: a collection and acquisition layer; a processing and network layer; and a storage, visualization, and analysis layer as shown in Fig.2., for example, in [26], the authors suggested an IoT-based remote monitoring system for solar power plants. They layered the proposed system into three basic layers, the first layer is the sensing layer, which consists of several sensors and a microcontroller. The middle level is responsible for the network and communication layer, where the collected data are transmitted to the last level. Finally, the application layer, where the received data are stored and presented to end-users via graphical user interfaces. The architecture and functionalities of IoT-enabled smart energy grid systems were examined in [27]. The authors presented a three-layer architecture suitable for the IoT-based smart power grid, consisting of a data collection layer, a data communication layer, and a data storage, processing, and visualization layer. However, many studies have proposed and designed IoT-based PV monitoring systems with different architecture layers, such as four-layer; five-layer; six-layer; and seven-layer architectures. In [28], the researchers developed an IoT-based energy management system for a grid-connected solar photovoltaic-powered DC residential building. This system is implemented for monitoring and controlling the applications and energy sources with a five-layer architecture: perception layer, network layer, energy management and control layer, application layer, and IoT services layer. A cloud-based IoT solution for remotely monitoring the amount of soiling on PV panels using an artificial neural network (ANN) was proposed in [15]. The designed system is based on a four-layer architecture: the perception layer, which contains sensors and physical devices to collect data; the network layer, responsible for establishing connections between devices, networks, and the cloud; the middleware layer, which serves as the system brain where the data received from the sensing layer are collected, processed, and stored; and lastly, the application layer, which consists of user interfaces, including mobile applications, browser-based applications, or any other visualization tools.



Fig. 2. The three-layer architecture of the IoT-based PV monitoring system

2.2. Hardware and software used in PV monitoring systems

The IoT system is described as a combination of hardware and software components, such as sensors, microcontrollers, communication modules, and cloud-based platforms. The selection of these components depends on various factors, including cost, scalability, security, and the specific requirements of the PV system being monitored and controlled. Over the past years, several hardware components have been proposed to design and implement IoT-based PV monitoring systems. These hardware components consist of sensors and data processing and transmission modules. The most commonly used electronic modules in PV monitoring systems include Arduino, ESP32, ESP8266, and Raspberry Pi [5]. On the other hand, numerous IoT software platforms are available for monitoring and controlling PV systems, including ThingsBoard, ThingSpeak, Eclipse, Node-Red, Thinger.io, and others. These open-source platforms offer flexibility, scalability, and cost-effectiveness for deploying IoT-based PV monitoring and management solutions [29].

A low-cost monitoring system for maximum power point tracking in a PV system was reported in [30]. This proposed system is based on an Arduino Mega 2560 and a Wi-Fi module ESP8266-01 as data acquisition and transmission modules, a website has been also designed to store and display the monitored data in real time. In [31], the authors proposed three IoT-embedded monitoring systems and implemented them in three grid-connected photovoltaic plants, using ESP8266 and ESP32 as data processing and transmission modules. A Raspberry Pi is used in [32] as the data gateway stage of a monitoring system applied to a small-scale prototype of an autonomous solar water pumping system. The authors used also InfluxDB for database storage and Grafana as data visualization software. In [33] a system for real-time data acquisition, monitoring, and control of self-generated energy at a remote location is presented. The authors proposed using an ESP32-S2 microcontroller to collect and process energy data, along with a Node-Red server for monitoring and controlling energy. An Arduino Nano, a Node MCU, and the ThingSpeak platform were used to control and monitor the performances of the dual-axis solar tracker system proposed in [34]. In [35], the authors designed and implemented a monitoring system for a grid-connected photovoltaic system using an Internet of Things solution based on a Raspberry Pi 4, and the Node-RED/Azure IoT platforms.

2.3. Communication network protocols

Communication network technologies play a crucial role in IoT systems. These technologies can be divided into infrastructure communication technologies, which connect networks and systems, such as Wi-Fi, Bluetooth/BLE, Zigbee, LoRa/LoRaWAN, GSM/GPRS, Sigfox, and others. Table 3. presents a comparison of IoT communication technologies used in IoT-based PV monitoring systems. Additionally, messaging protocols, which are responsible for data exchange between devices, applications, or the cloud. These protocols including HTTP, MQTT, CoAP, AMQP, and XMPP are listed and compared in Table 4. [36].

Table 2. A comparison of infrastructure communication technologies

Communication Technologies	Wi-Fi	Bluetooth/BLE	Zigbee	LoRa/LoRaWAN	GSM/GPRS
Network Type	LAN	PAN	PAN	LPWAN	WAN
Frequency	2.4, 5GHz	2.4GHz	2.4GHz	433/868 MHz 915 MHz 43MHz	850MHz-1.5GHz
Range	100-250m	100m	75m	2-15Km	+35Km
Data Rate	100-250Kbps	1Mbps	250Kbps	50Kbps	168Kbps
Power Consumption	High	Low	Very Low	Low	Very High

Table 3. A comparison of messaging communication protocols

Protocols	HTTP	MQTT	CoAP	AMQP	XMPP
Transport	TCP	TCP	UDP	TCP	TCP
Transport Port	80 / 443	1883 / 8883	5683 / 5684	5671 / 5672	5222
Message Pattern	Request / Response	Publish / Subscribe	Publish / Subscribe and Request / Response	Publish / Subscribe and Request / Response	Publish / Subscribe and Request / Response
Architecture	Client / Server	Tree	Tree	Star	Client / Server
Security	TLS/SSL	TLS	DTLS	SASL, TLS/SSL	SASL/TLS
Header Size	Undefined	2 bytes	4 bytes	8 bytes	Variable
Message Size	Undefined	Up to 256MB	64KB	Undefined	Undefined

2.4. Challenges and issues

The IoT-based PV monitoring systems provide enhanced reliability, improved energy efficiency, predictive maintenance capabilities, and greater accessibility for users to monitor and manage PV solar power systems. However, the performances of these systems are impacted by a range of challenges and issues, including compatibility, interoperability, scalability, security, and privacy [37, 38].

3.2.1 Compatibility and interoperability

IoT systems consist of multiple devices, including sensors, actuators, data processing modules, and data transmission modules, which are developed by different manufacturers. These devices often have varying characteristics and capabilities, such as different architectures, storage and processing capacities, operating voltages, and supported communication protocols. These heterogeneous characteristics and capabilities of the devices introduce challenges in ensuring continuous and stable communication between them and the central monitoring system, as well as in facilitating the seamless exchange of data.

3.2.2 Scalability

The increased implementation of IoT PV monitoring systems presents scalability challenges, particularly in data handling, transmission, storage, and energy management. As the PV system expands, the number of IoT devices increases, leading to an exponential rise in the volume of data generated. This growth complicates the collection, processing, transmission, and storage of this vast amount of data. Additionally, the increased device usage results in higher overall energy consumption. Furthermore, integrating new IoT devices and technologies with existing PV systems becomes increasingly complex as the scale grows.

3.2.3 Security and privacy

IoT-based PV systems use various communication technologies to establish connections between devices, gateways, and servers, enabling data transmission, storage, and system control. However, the lack of common communication standards leads to significant security and privacy challenges. Additionally, the heterogeneity of IoT devices complicates efforts to secure the system. The IoT devices in PV systems generate and transmit sensitive data, such as performance metrics and control signals, which can be exploited if not adequately protected. Ensuring the confidentiality and integrity of this data is a crucial challenge for IoT PV systems.

3 IoT monitoring system proposed

3.1 System description

The proposed IoT PV monitoring system aims include gathering, transmitting, storing, and visualizing data from a PV system. This monitored PV system comprises a polycrystalline PV module, a DC-DC boost converter (MT3608 module), which converts the lower output voltage of the PV module (6V) to another higher one (12V), and a 12V load (led strip lights) as shown in Fig.3. The IoT monitoring system is based on a three-layer architecture: (1) acquisition and collection layer; (2) network and processing layer; and (3) visualization and analysis layer (Fig.2).

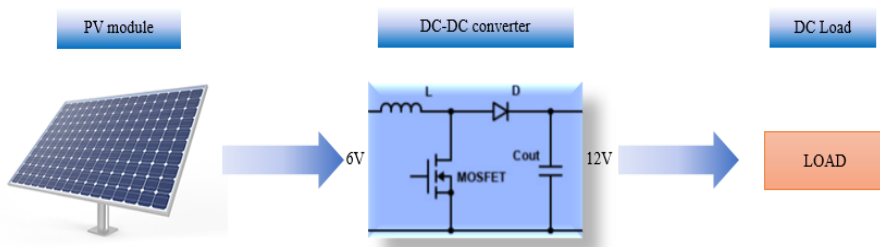


Fig. 3. PV system

Fig.4. presents the monitoring system configuration consisting of four sensors (two INA219 sensors, a DHT22 sensor, and a VEML7700 sensor) along with an ESP32 board. INA219 sensors acquire the electrical parameters including power, current, and voltage, for both the solar module and the load. they communicate with ESP32 through the I2C communication protocol interface. Ambient temperature and humidity are measured using a DHT22 sensor, connected to a digital pin on the ESP32. The VEML7700 is a sensor that measures light intensity and features an I2C communication interface for integration with the ESP32. The ESP32 board is a low-cost, low-power microcontroller with Wi-Fi and Bluetooth capabilities. The collected data is transmitted to the ThingsBoard platform via the MQTT protocol. In this setup, the ThingsBoard platform functions as an MQTT broker, receiving data published by the MQTT client (ESP32) for storage and visualization on the created dashboard.

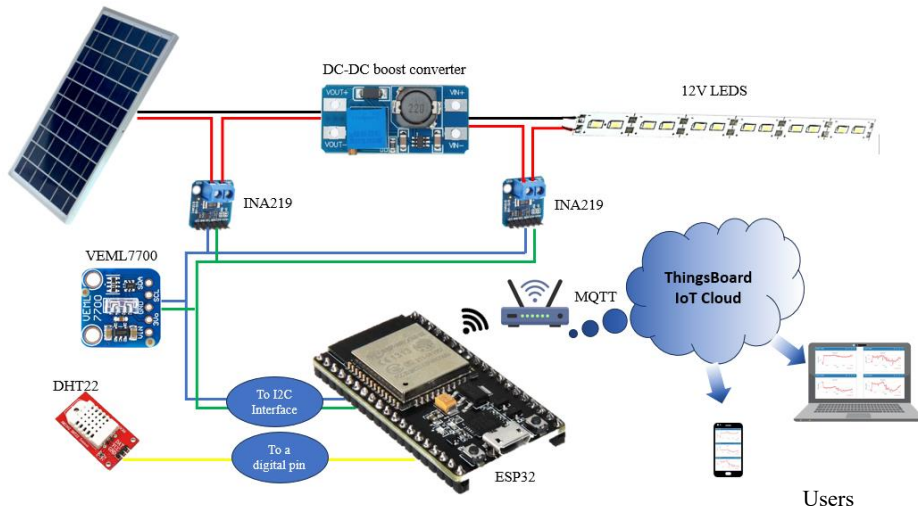


Fig. 4. Bloc Diagram of the proposed IoT PV monitoring system

3.2 System components

3.2.1 Sensors

Table 4 presents the sensor characteristics used in the proposed PV monitored system.

Table 4. The sensor characteristics used in the proposed system

Sensor	Measuring parameters	Operating voltage	Measuring range	Resolution
INA219	Current, voltage, power	3 to 5.5V	Up to 3.2A / 0 to 26V	±0.8mA
DHT22	Temperature, humidity	3.3 to 6V	-40 to 80°C / 0 to 100%	±0.5°C / ±2%RH
VEML7700	Light intensity	2.5 V to 3.6 V	0 to 140 000lx	0.0042lx

3.2.2 ESP32 microcontroller

In this study, the ESP32 is used as a microcontroller due to its low cost, low power consumption, and ease of integration into IoT projects. It includes Wi-Fi and Bluetooth wireless functions and a dual-core processor. The ESP32 supports a wide variety of peripherals like ADC (analog to digital converter), DAC (digital to analog converter), SPI (Serial Peripheral Interface), UART (universal asynchronous receiver/transmitter), I2C (Inter-Integrated Circuit), I2S (Integrated Inter-IC Sound), RMII (Reduced Media-Independent Interface), PWM (pulse width modulation), and more. The ESP32 operates on the Tensilica Xtensa Dual-Core 32-bit LX6 microprocessor. It is compatible with Arduino IDE, allowing it to function like an Arduino board, and can also be programmed using MicroPython firmware [39].

3.2.3 ThingsBoard IoT platform

ThingsBoard is an open-source IoT platform, that provides data collection, processing, visualization, rule engine capabilities, and device management. ThingsBoard builds on the Java 8 platform and enables device connectivity via standard IoT protocols including MQTT, CoAP, and HTTP. It supports three different database options: SQL, NoSQL, and Hybrid databases. ThingsBoard offers three IoT platforms: the Community Edition, which is a free and entirely open-source platform, the Professional Edition, which is an advanced IoT platform with more advanced features, and the Cloud, which is a platform as a service. In this study, we used the Community Edition [40].

3.3 Implementation methodology

The DC-DC boost converter is necessary to increase the PV output voltage from 6V to 12V to supply the 12V load. Two INA219 sensors are employed: one attached to the PV output to measure the current, voltage, and power, and the other connected to the converter output to monitor the load's current, voltage, and power. The DHT22 and VEML7700 sensors are positioned near the PV module to gather environmental parameters. INA219 sensors and VEML7700 sensor are connected with ESP32 via the I2C interface using three different addresses 0x40, 0x41, and 0x10 respectively. All sensors were verified and calibrated precisely. The current and voltage measurements obtained from the INA219 sensors can be displayed and compared with the readings of a standard multimeter (PeakTech 2005DMM). A lux meter (LX-101 LUX METER) was used to calibrate The VEML7700 sensor, while the DHT22 sensor was calibrated using a standard thermometer.

Fig.5. shows the flowchart of the proposed IoT-based PV monitoring system. The algorithm was written and uploaded to the ESP32 microcontroller using the Arduino IDE.

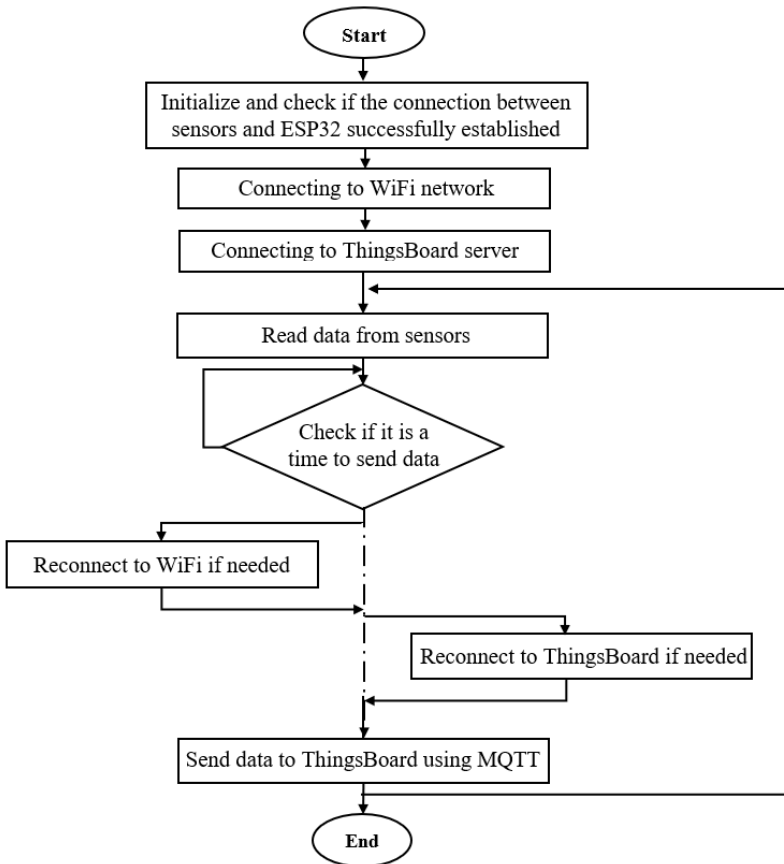


Fig. 5. The flowchart of the proposed IoT-based PV monitoring system

3.4 Results and Discussion

The experimental setup of the proposed system is depicted in Fig.6. All the previously described hardware designs have been successfully implemented in this configuration. The PV system was monitored and tracked by an IoT system, which

allows the collection, processing, transmission, storage, and visualization of electrical and environmental data including current, voltage, and power generated by the PV module and consumed by the load, as well as ambient temperature, humidity, and light intensity. These data are collected by sensors and then transmitted using an ESP32 microcontroller to the ThingsBoard platform via MQTT communication protocol over a WiFi network connection.

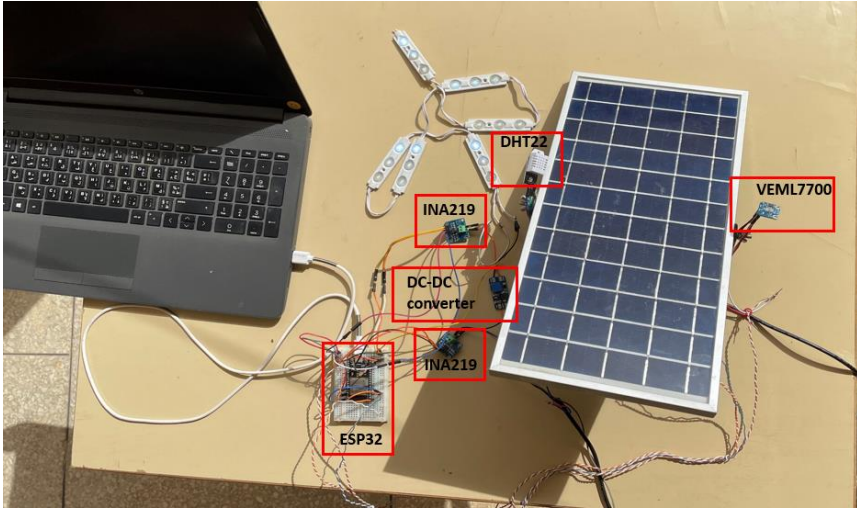


Fig. 6. The experimental setup of the proposed system

The ThingsBoard platform enables the creation of multiple rich dashboards for real-time data visualization and remote device control. Our created dashboards as shown in Fig.7., include Timeseries Line Charts for voltages, currents, powers, and light intensity (Fig.8. a,b,c,d). Additionally, the dashboards feature two cards that display the latest and historical values of temperature and humidity (Fig.9.). Furthermore, a timeseries table for all monitored data (Fig.10.).

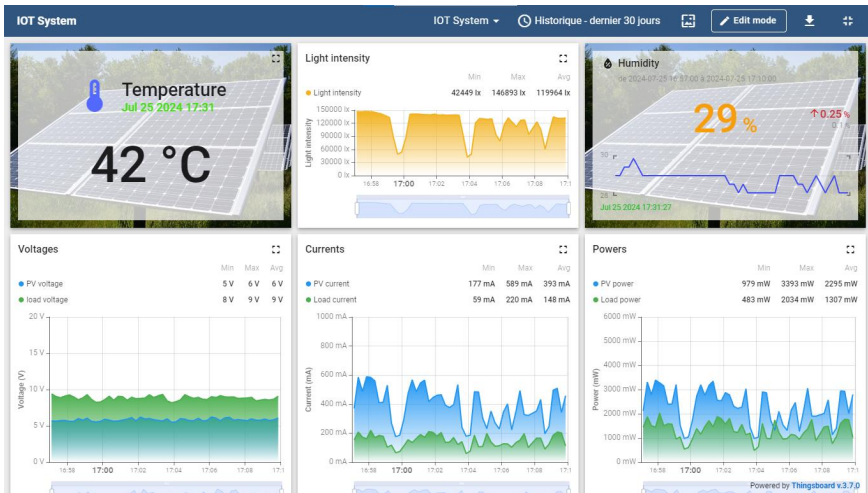


Fig. 7. Created dashboard

The proposed IoT system is a low cost and low power system owing to the hardware and software components used. This system has been thoroughly tested and implemented successfully. Data are collected and transmitted to ThingsBoard platform at intervals of fifteen seconds. During this monitoring period, we notice as shown in Fig.8. (d) that the irradiation level drops three times at 16:59:30, 17:03:45, and 17:08:45, respectively, which can be attributed to the presence of clouds. These drops of irradiation directly affect the PV power produced as shown in Fig.8. (c).



Fig. 8. Timeseries Line Charts for: (a) Voltages, (b) Currents, (c) Powers, and (d) Light intensity

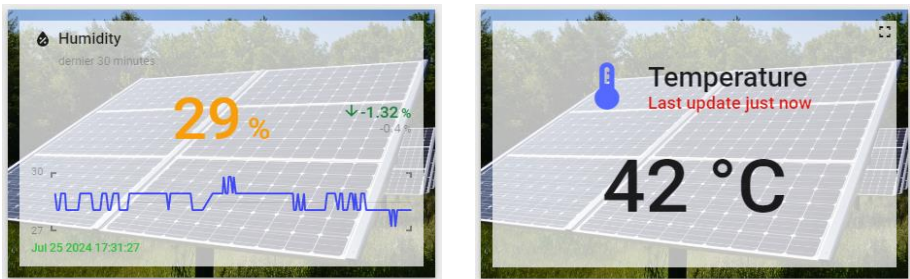


Fig. 9. Temperature and humidity display cards

Timestamp ↑	Temperature	Humidity	Light intensity	PV current	Load current	PV voltage	Load voltage	PV power	Load power
2024-07-25 16:57:00	41 °C	29 %	147777 lx	433 mA	194 mA	6 V	9 V	2504 mW	1825 mW
2024-07-25 16:57:08	41 °C	29 %	145222 lx	308 mA	114 mA	6 V	9 V	1727 mW	1067 mW
2024-07-25 16:57:17	41 °C	29 %	145638 lx	583 mA	199 mA	6 V	9 V	3323 mW	1821 mW
2024-07-25 16:57:25	40 °C	29 %	146306 lx	588 mA	217 mA	6 V	9 V	3298 mW	1934 mW
2024-07-25 16:57:33	41 °C	30 %	146725 lx	479 mA	218 mA	6 V	9 V	2753 mW	1865 mW
2024-07-25 16:57:41	41 °C	29 %	147061 lx	495 mA	126 mA	6 V	9 V	2828 mW	1159 mW
2024-07-25 16:57:50	41 °C	29 %	145888 lx	592 mA	216 mA	6 V	9 V	3428 mW	1899 mW
2024-07-25 16:57:58	41 °C	30 %	147187 lx	586 mA	106 mA	6 V	9 V	3357 mW	1000 mW
2024-07-25 16:58:06	41 °C	30 %	145888 lx	584 mA	220 mA	6 V	9 V	3279 mW	2034 mW

Fig. 10. Timeseries table for all monitored data

4 Conclusion

In this paper, we investigated an IoT-based photovoltaic monitoring system, offering a comprehensive overview of the various architectures, software and hardware platforms, and communication network technologies employed in these systems. Our investigation highlighted the existing challenges and issues, including compatibility, interoperability, scalability, security, and privacy. Additionally, a low-cost, low-power monitoring system is designed to monitor a PV system consisting of a PV panel, a DC-DC boost converter, and a load. This proposed system provides the collection, processing, transmission, storage, and visualization of electrical and environmental data including current, voltage, and power generated by PV module and consummated by load, as well as ambient temperature, humidity, and light intensity. In addition, a set of sensors collects these data and then transmits them using an ESP32 microcontroller to the ThingsBoard platform via MQTT communication protocol over a WiFi network connection.

Acknowledgments

The first author would like to thank the National Center for Scientific and Technical Research (CNRST) for the financial support received as part of the “PhDAssociate Scholarship–PASS” Program.

References

1. E. Kabir, P. Kumar, S. Kumar, A. A. Adedolun, and K.-H. Kim, Solar energy: Potential and future prospects, *Renewable and Sustainable Energy Reviews* **82**, 894 (2018).
2. A. Al-Sharafi, A. B. Ahmadullah, G. Hassan, H. Al-Qahtani, A. A. Abubakar, and B. S. Yilbas, Influence of environmental dust accumulation on the performance and economics of solar energy systems: A comprehensive review, *Cleaner Energy Systems* **8**, 100125 (2024).
3. S. Nižetić, P. Šolić, D. López-de-Ipiña González-de-Artaza, and L. Patrono, Internet of Things (IoT): Opportunities, issues and challenges towards a smart and sustainable future, *Journal of Cleaner Production* **274**, 122877 (2020).
4. D. C. Nath, I. Kundu, A. Sharma, P. Shivhare, A. Afzal, M. E. M. Soudagar, and S. G. Park, Internet of Things integrated with solar energy applications: a state-of-the-art review, *Environ Dev Sustain* (2023).
5. S. Ansari, A. Ayob, M. S. H. Lipu, M. H. M. Saad, and A. Hussain, A Review of Monitoring Technologies for Solar PV Systems Using Data Processing Modules and Transmission Protocols: Progress, Challenges and Prospects, *Sustainability* **13**, 8120 (2021).
6. M. M. Rahman, J. Selvaraj, N. A. Rahim, and M. Hasanuzzaman, Global modern monitoring systems for PV based power generation: A review, *Renewable and Sustainable Energy Reviews* **82**, 4142 (2018).
7. S. Kirmani, A. Mazid, I. A. Khan, and M. Abid, A Survey on IoT-Enabled Smart Grids: Technologies, Architectures, Applications, and Challenges, *Sustainability* **15**, 717 (2022).
8. C. K. Rao, S. K. Sahoo, and F. F. Yanine, A literature review on an IoT-based intelligent smart energy management systems for PV power generation, *Hybrid Advances* **5**, 100136 (2024).
9. L. O. Aghenta, M. Tariq Iqbal, and Department of Electrical and Computer Engineering, Faculty of Engineering and Applied Science, Memorial University of Newfoundland (MUN), St. John’s, NL A1B 3X5, Canada, Design and implementation of a low-cost, open source IoT-based SCADA system using ESP32 with OLED, ThingsBoard and MQTT protocol, *AIMS Electronics and Electrical Engineering* **4**, 57 (2020).
10. Y. Cheddadi, H. Cheddadi, F. Cheddadi, F. Errahimi, and N. Es-sbai, Design and implementation of an intelligent low-cost IoT solution for energy monitoring of photovoltaic stations, *SN Appl. Sci.* **2**, 1165 (2020).

11. P. De Arquer Fernández, M. Á. Fernández Fernández, J. L. Carús Candás, and P. Arboleya Arboleya, An IoT open source platform for photovoltaic plants supervision, *International Journal of Electrical Power & Energy Systems* **125**, 106540 (2021).
12. G. Boubakr, F. Gu, L. Farhan, and A. Ball, Enhancing Virtual Real-Time Monitoring of Photovoltaic Power Systems Based on the Internet of Things, *Electronics* **11**, 2469 (2022).
13. W. A. Jabbar, S. Annathurai, T. A. A. Rahim, and M. F. Mohd Fauzi, Smart energy meter based on a long-range wide-area network for a stand-alone photovoltaic system, *Expert Systems with Applications* **197**, 116703 (2022).
14. M. A. Sheba, D. A. Mansour, and N. H. Abbasy, A new low-cost and low-power industrial internet of things infrastructure for effective integration of distributed and isolated systems with smart grids, *IET Generation Trans & Dist* **17**, 4554 (2023).
15. M. Ul Mehmood, A. Ulasayar, W. Ali, K. Zeb, H. S. Zad, W. Uddin, and H.-J. Kim, A New Cloud-Based IoT Solution for Soiling Ratio Measurement of PV Systems Using Artificial Neural Network, *Energies* **16**, 996 (2023).
16. M. A. A. Radia, M. K. E. Nimr, and A. S. Atlam, IoT-based wireless data acquisition and control system for photovoltaic module performance analysis, *E-Prime - Advances in Electrical Engineering, Electronics and Energy* **6**, 100348 (2023).
17. A. Asnil, K. Krismadinata, I. Husnaini, H. Hazman, and E. Astrid, Real-Time Monitoring System Using IoT for Photovoltaic Parameters, *TEM Journal* **13**16 (2023).
18. R. Muñiz, R. Del Coso, F. Nuño, P. J. Villegas, D. Álvarez, and J. A. Martínez, Solar-Powered Smart Buildings: Integrated Energy Management Solution for IoT-Enabled Sustainability, *Electronics* **13**, 317 (2024).
19. Md. M. Islam, S. Nooruddin, F. Karray, and G. Muhammad, Internet of Things: Device Capabilities, Architectures, Protocols, and Smart Applications in Healthcare Domain, *IEEE Internet Things J.* **10**, 3611 (2023).
20. M. A. Caraveo-Cacep, R. Vázquez-Medina, and A. Hernández Zavala, A survey on low-cost development boards for applying cryptography in IoT systems, *Internet of Things* **22**, 100743 (2023).
21. Y. Saleem, N. Crespi, M. H. Rehmani, and R. Copeland, Internet of Things-Aided Smart Grid: Technologies, Architectures, Applications, Prototypes, and Future Research Directions, *IEEE Access* **7**, 62962 (2019).
22. R. Khan, S. U. Khan, R. Zaheer, and S. Khan, *Future Internet: The Internet of Things Architecture, Possible Applications and Key Challenges*, in *2012 10th International Conference on Frontiers of Information Technology (IEEE, Islamabad, Pakistan, 2012)*, pp. 257–260.
23. A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications, *IEEE Commun. Surv. Tutorials* **17**, 2347 (2015).
24. N. M. Kumar, A. Dash, and N. K. Singh, *Internet of Things (IoT): An Opportunity for Energy-Food-Water Nexus*, in *2018 International Conference on Power Energy, Environment and Intelligent Control (PEEIC)* (IEEE, Greater Noida, India, 2018), pp. 68–72.
25. G. Mokhtari, A. Anvari-Moghaddam, and Q. Zhang, A New Layered Architecture for Future Big Data-Driven Smart Homes, *IEEE Access* **7**, 19002 (2019).
26. S. Adhya, D. Saha, A. Das, J. Jana, and H. Saha, *An IoT Based Smart Solar Photovoltaic Remote Monitoring and Control Unit*, in *2016 2nd International Conference on Control, Instrumentation, Energy & Communication (CIEC)* (IEEE, Kolkata, India, 2016), pp. 432–436.
27. S. M. A. A. Abir, A. Anwar, J. Choi, and A. S. M. Kayes, IoT-Enabled Smart Energy Grid: Applications and Challenges, *IEEE Access* **9**, 50961 (2021).
28. N. D. Chinnathambi, K. Nagappan, C. R. Samuel, and K. Tamilarasu, Internet of things-based smart residential building energy management system for a grid-connected solar photovoltaic-powered DC residential building, *Intl J of Energy Research* **46**, 1497 (2022).
29. T. Domínguez-Bolaño, O. Campos, V. Barral, C. J. Escudero, and J. A. García-Naya, An overview of IoT architectures, technologies, and existing open-source projects, *Internet of Things* **20**, 100626 (2022).
30. N. Rouibah, L. Barazane, A. Mellit, B. Hajji, and A. Rabhi, *A Low-Cost Monitoring System for Maximum Power Point of a Photovoltaic System Using IoT Technique*, in *2019 International Conference on Wireless Technologies, Embedded and Intelligent Systems (WITS)* (IEEE, Fez, Morocco, 2019), pp. 1–5.
31. R. I. S. Pereira, S. C. S. Jucá, and P. C. M. Carvalho, IoT embedded systems network and sensors signal conditioning applied to decentralized photovoltaic plants, *Measurement* **142**, 195 (2019).
32. F. J. Gimeno-Sales, S. Orts-Grau, A. Escribá-Aparisi, P. González-Altozano, I. Balbastre-Peralta, C. I. Martínez-Márquez, M. Gasque, and S. Seguí-Chilet, PV Monitoring System for a Water Pumping Scheme with a Lithium-Ion Battery Using Free Open-Source Software and IoT Technologies, *Sustainability* **12**, 10651 (2020).
33. M. J. A. Baig, M. T. Iqbal, M. Jamil, and J. Khan, Design and implementation of an open-Source IoT and blockchain-based peer-to-peer energy trading platform using ESP32-S2, Node-Red and, MQTT protocol, *Energy Reports* **7**, 5733 (2021).
34. P. Muthukumar, S. Manikandan, R. Muniraj, T. Jarin, and A. Sebi, Energy efficient dual axis solar tracking system using IOT, *Measurement: Sensors* **28**, 100825 (2023).
35. J. F. Supo, P. Y. Puma, J. M. Ramos, and N. J. Beltrán, Implementation of a monitoring system for a photovoltaic installation based on IoT technology, *J. Phys.: Conf. Ser.* **2538**, 012003 (2023).
36. E. Al-Masri, K. R. Kalyanram, J. Batts, J. Kim, S. Singh, T. Vo, and C. Yan, Investigating Messaging Protocols for the Internet of Things (IoT), *IEEE Access* **8**, 94880 (2020).

37. M. Azrou, J. Mabrouki, A. Guezzaz, and A. Kanwal, Internet of Things Security: Challenges and Key Issues, *Security and Communication Networks* **2021**, 1 (2021).
38. Md. O. Qays, I. Ahmad, A. Abu-Siada, Md. L. Hossain, and F. Yasmin, Key communication technologies, applications, protocols and future guides for IoT-assisted smart grid systems: A review, *Energy Reports* **9**, 2440 (2023).
39. Espressif, *Espressif*, <https://www.espressif.com/>, (Accessed 07/20/2024).
40. Thingsboard.io, *Thingsboard IoT Platform*, <https://thingsboard.io/>, (Accessed 07/21/2024).