Smart monitoring technique for solar cell systems using internet of things based on NodeMCU ESP8266 microcontroller

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Article Info

ABSTRACT

Rapidly and remotely monitoring and receiving the solar cell systems status parameters, solar irradiance, temperature, and humidity, are critical issues in enhancement their efficiency. Hence, in the present article an improved smart prototype of internet of things (IoT) technique based on embedded system through NodeMCU ESP8266 (ESP-12E) was carried out experimentally. Three different regions at Egypt; Luxor, Cairo, and El-Beheira cities were chosen to study their solar irradiance profile, temperature, and humidity by the proposed IoT system. The monitoring data of solar irradiance, temperature, and humidity were live visualized directly by Ubidots through hypertext transfer protocol (HTTP) protocol. The measured solar power radiation in Luxor, Cairo, and El-Beheira ranged between 216-1000, 245-958, and 187-692 W/m^2 respectively during the solar day. The accuracy and rapidity of obtaining monitoring results using the proposed IoT system made it a strong candidate for application in monitoring solar cell systems. On the other hand, the obtained solar power radiation results of the three considered regions strongly candidate Luxor and Cairo as suitable places to build up a solar cells system station rather than El-Beheira.

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1. INTRODUCTION

Enriching the industrial revolution without harming the environment, especially with the increasing climate changes, requires increased reliance on clean sources of electrical energy. Solar cell systems are one of the sustainable and green energy sources, the demand for which is increasing day by day [1]–[3]. Solar cell systems face many challenges, starting from the materials to manufacture the cells themselves to the rapid monitoring of the environmental conditions surrounding the installed solar cell systems, such as shading, temperature, and humidity. Monitoring these variables and receiving their results quickly and accurately accelerates taking appropriate procedures to repair any defect in solar systems during operation. In solar cell systems, the accuracy of measuring the solar power radiation, humidity, and temperature change and receiving is the backbone of harvesting the maximum output from it [4]–[6]. Internet of things (IoT) is one of the most efficient modern tools that proposed to monitor the solar cell systems [7]–[11]. IoT works effectively to connect physical gadgets quickly and easily to the cloud, which in turn works on exchanging the data freely that is facilitating getting the results and interacting with the gadgets via the Internet. The IoT has enhanced the

development of solar systems modeling and control, and the effectiveness of data prediction and acquisition [7]–[13]. The Internet of Things facilitates and accelerates data acquisition from embedded systems for analysis and speeds remote of devices associated with those systems with minimal human involvement [14], [15]. Choosing the appropriate and low-cost embedded systems strongly supports the performance of IoT systems. NodeMCU is one of the most popular embedded systems that support IoT systems in monitoring solar cell systems. Since solar cells are very sensitive to environmental changes, such as shadow, humidity, and temperature, which directly reduce the output power of solar cell systems, the monitoring and tracking systems of solar cell systems parameters are constantly used to evaluate the status of solar power plants. Monitoring systems for tracking solar cell parameters, which are constantly being developed, require further studies as they are still complex and have a high production cost, especially in small and medium-scale solar cell plants. Also, the advantage of providing a system with the ability to store the measured solar cell parameters to compare changes is an important requirement in monitoring systems [16]. In 2020, Cheddadi [17] implemented a low cost and open-source internet of things solution for real-time monitoring of environmental conditions of solar power stations. Their proposed system provides an alert for remote users for monitoring any deviation in solar power generation. Dong *et al.* [18] implemented in 2021 an embedded system based on IoT and neural network processing to collect the real-time video image of the solar cell system and detect the defects of solar panels in real-time. They found that their embedded system improves the performance of solar photovoltaic cell systems and reduces operation and maintenance costs. They found that the accuracy rate of their implemented design was 93.75%. In 2022, Andal and Jayapal [19] implemented a low-cost IoT controller for remotely monitoring power generated and consumed by PV/wind/battery. They used multi-function sensors to monitor the generated power and transmitted the data to various servers in the cloud via an internet connection. The authors used solar and wind energy to construct a prototype, with an Arduino microcontroller regulating and directing power transmission between slave nodes to guarantee a successful outcome. The authors recommend their proposed IoT smart communication system as a helpful technique for providing real-time monitoring and control of smart microgrids. In 2023, Hamied *et al.* [20] constructed a low-cost monitoring system based on IoT for an off-grid photovoltaic (PV) system. The authors created a web page to visualize the measured data. The total cost of the built system was 73 euros and consumed 13.5 Wh daily.

Hence and herein, a cheap and simple IoT technique was used to monitor remotely the solar system. A NodeMCU ESP8266 (ESP-12E) system was used to measure the PV status parameters; solar irradiance, temperature, and humidity and the obtained data were sent by a proposed system based IoT techniques. To save energy and reduce maintenance costs, the proposed monitoring system was built and programmed to work smartly with sunlight. The built system also had the advantage of storing measured parameters in the event of any loss in receiving the data to ensure that none of them were lost. The rest of the paper is categorized as follows: Section 2 explains the experimental procedures and the implemented system; Section 3 explains the results and discusses them in detail; and finally, the article in its last section presented the obtained conclusions.

2. METHOD

A cheap and simple smart IoT system was implemented for monitoring and sending the solar cell system status parameters; solar irradiance, temperature, and humidity. An embedded system based on NodeMCU ESP8266 (ESP-12E) integrated with different sensors was used to monitor and sense the PV status parameters, as shown in Figure 1. The sensed data was sent through ESP8266 (ESP-12E) linked by router. Additionally, the monitoring data was live displayed on the Ubidots platform, which is characterized by accessed remotely and in real-time via any device, such as laptops, PCs, and smartphones. Finally, the proposed system works as a smart system that starts running with sunrise and ends with sunset. First, the whole monitoring system was fed through 12-volt feed system contains a solar panel, charger controller, and a PV battery, as shown in Figure 2(a). NodeMCU ESP8266 (ESP-12E) is used as an open-source firmware to build IoT-based systems. NodeMCU ESP8266 (ESP-12E) is distinguished from its counterparts because ESP8266 (ESP-12E) Wi-Fi is built-in and does not need to be added as an external component. It is also characterized by its low cost and power consumption and can be simply programmed. The NodeMCU was programmed to accurately analyze the incoming solar irradiance, temperature, and humidity signals and send them via ESP8266 (ESP-12E) Wi-Fi. The ESP8266 (ESP-12E) Wi-Fi module is a system-on-a-chip (SoC) integrates with TCP/IP protocol stack giving the microcontroller access to the Wi-Fi network. The ESP8266 (ESP-12E) is capable to be either a host application (webserver) or a Wi-Fi client, which connects to local or online servers. Here, it was used as a Wi-Fi client. The used light dependent resistor (LDR) was connected to NodeMCU ESP8266 analog pins A0 to act as the input for the system, as shown in Figure 2(b). LDR was connected with fixed resistance and then connected to the NodeMCU ESP8266 to read solar power radiation according to (1) [21].

$$\text{solar power radiation} = \left(\frac{\text{lux}}{683}\right) * 345.396656 \qquad (1)$$

Sensing temperature and humidity was carried out through a cheap and accurate digital DHT11 senor (Temperature accuracy ±2 °C and humidity accuracy $\pm5\%$), which is connected to a capacitive humidity sensor and a thermistor. The DHT11 sensor was connected to the NodeMCU ESP8266 (ESP-12E) digital pins D1 as shown in Figure 2(b). The digital signals of the sensor are fairly easy to read using any microcontroller. The soft operation of the system is developed according to the flow chart in Figure 3.
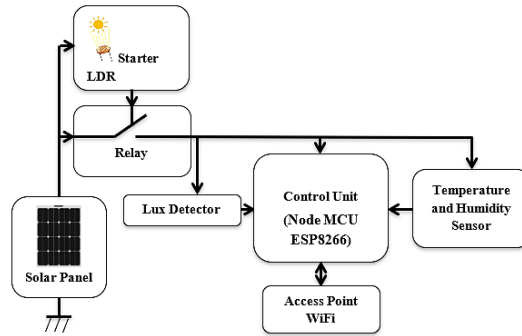
Figure 1. The block diagram of the proposed system

Figure 2. The proposed IoT system (a) the feeding system and (b) implemented circuit diagram
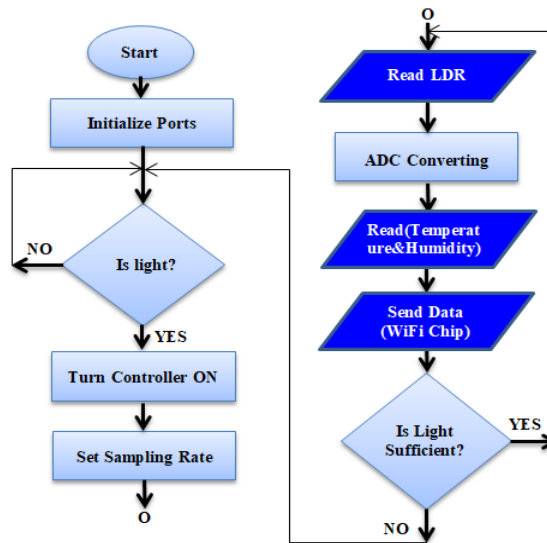
Figure 3. System procedure flow chart

According to Figure 3, the constructed system begins to search for sufficient sunlight (≥60 lux) through the LDR starter, repeating the research (is light?) until sufficient light is achieved for operation. The LDR starter ordered the relay to start the feeding of the microcontrollers and sensors (turn the controller on) from the PV system. The sampling rate, which refers to the measuring time rate is adjusted on the code (set sampling rate). Then, radiation and temperature and humidity sensors start recording the PV status parameters (irradiance, temperature, and humidity) and sending the data via Wi-Fi to the Ubidots platform. The system continues to repeat the measuring and sending the data until there is not enough light to operate (is light sufficient? <60 lux). The Arduino integrated development environment (Arduino IDE) is used to write and upload the computer code to the physical board (NodeMCU). USB driver CP2102 was used to connect between the NodeMCU board and computer. A router was used to receive the obtained data from the NodeMCU ESP8266 (ESP-12E) and send it through an IP address. An account was created on Ubidots via the HTTP protocol for facilitating the rapidly receiving and displaying the results. The library of HTTP Ubidots ESP8266 (ESP-12E) was installed on Arduino IDE. The obtained Token ID from Ubidots is fed into the code to support the results display authority.

The practical implemented system, which consist of a solar panel, charger controller, a PV battery, LM7805CT regulator, smart operating system, NodeMCU ESP8266 (ESP-12E), the sensors, is shown in Figure 4. The LM7805CT regulator connected with capacitors for smoothing and two diodes for polarity and regulator protection. The smart operating system consists of a photo resistor accompanied with 5 V relay driven by BC547BP transistor for a day/system operation starter. The smart operating system automatically controls of the input power of the monitoring system depending on solar irradiance through the relay. In the experimental implemented design, the PV battery output is connected to the regulator, which in turn is connected to the smart operating system and the NodeMCU ESP8266 (ESP-12E). The radiation sensor feeds from NodeMCU, while temperature and humidity sensor were fed from the output of smart operating system to avoid its effect on the system performance. In the same respect, in order to avoid the outage in data transfer through the router, the router fed directly through the PV battery.

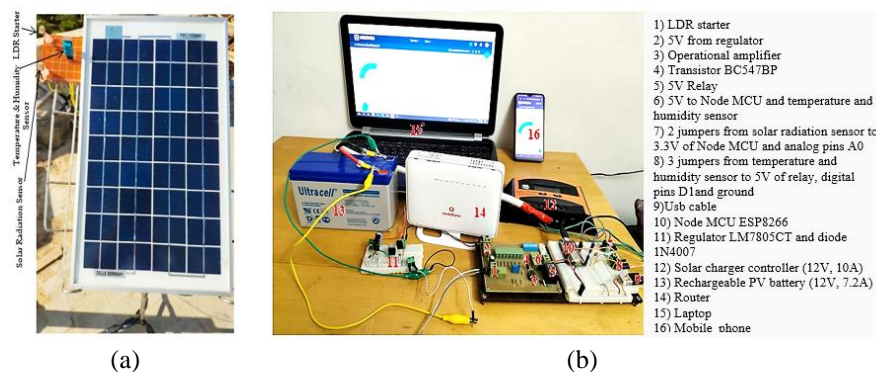(a)   (b)

Figure 4. The implemented IoT prototype (a) the installed PV panel, LDR starter, temperature and humidity sensor, and solar irradiance sensor and (b) the practical control system

3. RESULTS AND DISCUSSION

For examining the proposed IoT system reliability and carrying out a local surveying study on the most suitable locations for installing solar cell power stations, three different solar irradiance regions were selected; Luxor with high solar copious, El-Beheira with coastal weather, and Cairo with moderate weather [22], [23]. The measured results were received using IoT system based on NodeMCU ESP8266 (ESP-12E) through the common HTTP protocol. Figure 5 shows the live results of solar power radiation, temperature, and humidity that were measured during a solar day (6 am to 7 pm) and transmitted using the proposed IoT system. The received results of solar power radiation, temperature, and humidity are displayed in Figure 6. It is clearly observed that the solar power irradiance of Luxor is the highest followed by Cairo then El-Beheira, as shown in Figures 6(a). Luxor is the clearest sky, has the most minor dust, and is the equator nearest city compared to Cairo and El-Beheira. On the other hand, Luxor city has almost no industrial factories, which directly affects the solar profile through the environmental pollution. The lowest solar profile of El-Beheira is due to being a coastal city with variable weather and is usually cloudy. Although Cairo weather is close to Luxor, the spread out of the factories in and around it affects the solar irradiance profile. The received temperature and humidity using the proposed IoT system are shown in Figure 6(b) and (c). It is noticeable that the behavior of both temperature and humidity is completely harmonious with the behavior of solar

power radiation. Humidity is a powerful factor affecting the performance of solar cells, through its direct effect on solar power, in addition to the formation of a thin layer of water vapor on the surface of the cell [15], [17], [19]. Hence, the low value of moisture in Luxor reflects positively on the performance of the solar cells and hence the increase in their output power in contrast to the El-Beheira.
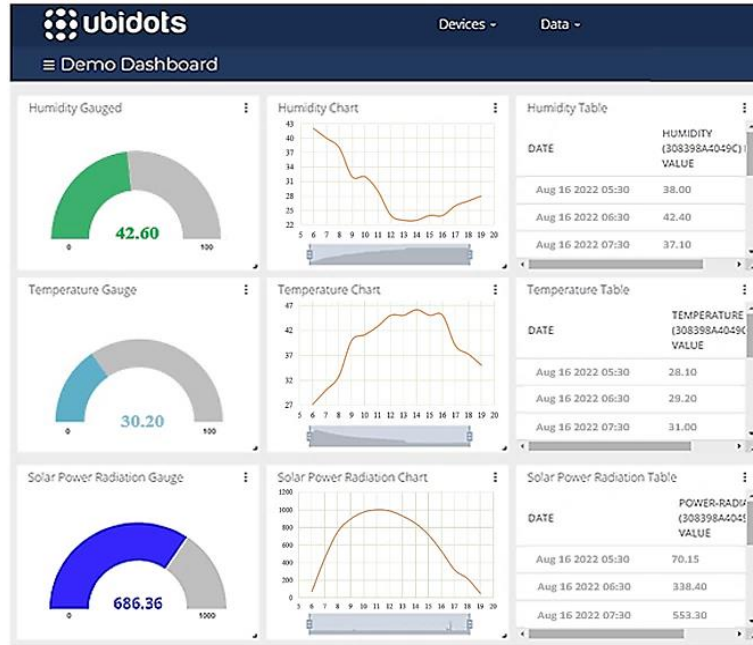

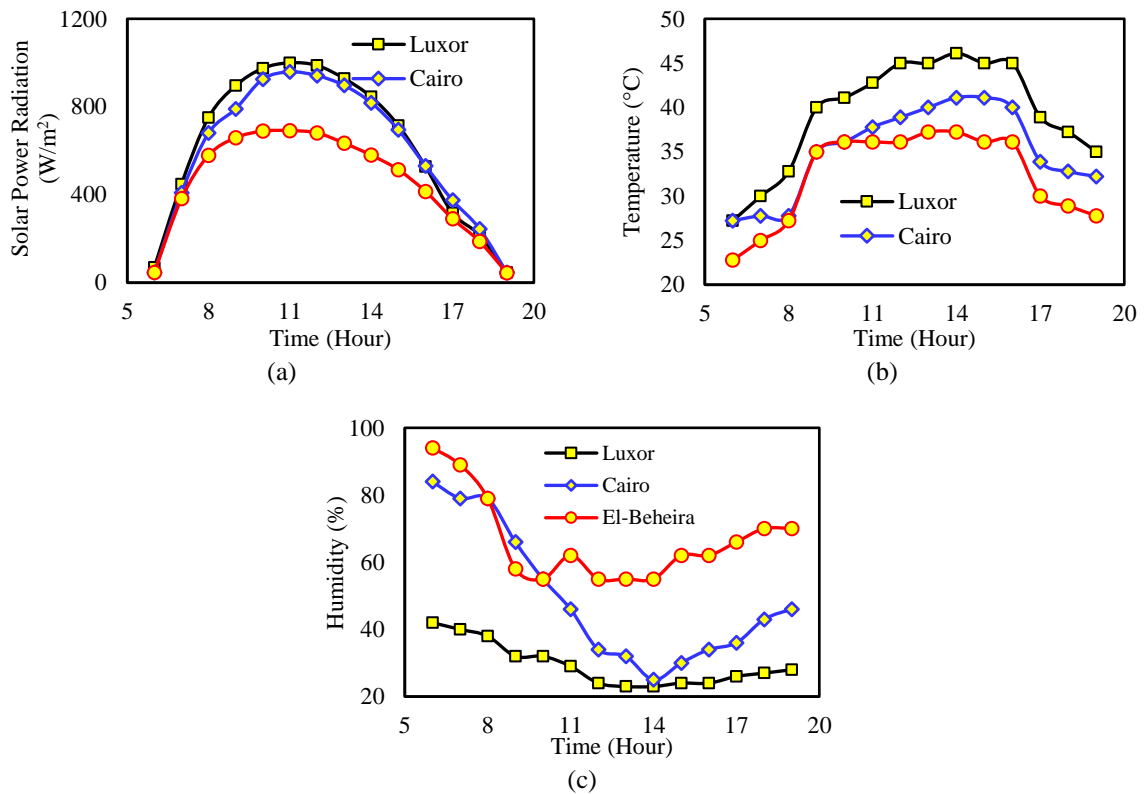Figure 5. The obtained solar power radiation, temperature, humidity result of the proposed using IoT system

Figure 6. Measured (a) solar power radiation, (b) temperature, and (c) humidity in the studied regions

Finally, to assess the efficiency of the proposed smart IoT system in monitoring the parameters of the PV status and its economic feasibility, the implemented system was characterized by the advantages: i) cost-effective and easy to maintain; ii) low-consumed power and feeds directly from the PV system; iii) measuring the solar irradiance, temperature, and humidity simultaneously; and iv) displaying the measured data in live profiles (curves and tables) on a webpage, making it easy to access the data at any time remotely. However, the system has two limitations, which are i) the limit of the distance of the Wi-Fi module and ii) the security of measured data. On the other hand, the reliance of the implemented strategy in the proposed system on NodeMCU ESP8266(ESP-12E) distinguishes it from its peers, which depend on Arduino [24], [25] (Uno, Nano, Mega), field-programmable gate array (FPGA) [26], [27], and Raspberry Pi [28]–[30] in its low cost, ease of programming, and availability. Table 1 summarizes the comparison between available previously designed IoT-based systems for monitoring the PV systems in the 2018-2023 period and the implemented IoT system in our article. The carried-out comparison focused on the available data of the used microcontroller, transceiver, cost, and the monitoring parameters. Finally, according to the listed comparison in Table 1, the proposed IoT monitoring system in our work is considered the lowest cost, in addition to the simplicity of its components. Additionally, it has a built-in Wi-Fi module, which makes it less energy-consuming and gives it several advantages over its peers.

Table 1. A comparison between the implemented smart IoT system and the available previously designed IoT-based systems

Year [Ref.]		Controller		Cost	Monitored parameters
	Board	Built-in Wi-Fi?	Wi-Fi Transceiver	(€)	
2018 [30]	Arduino Uno	No	Wireless: Ethernet	300.71	PV current & voltage, solar irradiance, temperature, and others
2019 [31]	Raspberry PI	Yes	LoRa	39.26	Solar irradiance, temperature, and PV current, voltage, & power
2020 [32]	Arduino Mega	No	Wireless: ESP8266	63.04	Solar irradiance, temperature, duty cycle, and PV current, voltage, & power
2022 [33]	Arduino Nano	No	LoRa	18.72	Solar irradiance, temperature, and PV current & voltage
2023 [34]	Arduino Mega	No	NodeMCU ESP8266	–	Light intensity, temperature, and PV current & voltage
Our work	NodeMCU	Yes	ESP8266(ESP-12E)	8.65	Solar irradiance, temperature, humidity

4.   CONCLUSION

An extensive study was conducted on a developed IoT system based on an embedded system using NodeMCU ESP8266 (ESP-12E) in order to monitor solar cell systems and the rapid of receiving the results of solar power radiation, temperature, and humidity. The proposed system is characterized by its simplicity and low cost, consisting of an integrated control board, NodeMCU, and Wi-Fi module ESP8266 (ESP-12E) as a built-in unit. The proposed system succeeded in displaying a live profile of all the parameters of the installed solar cell system; solar power radiation, temperature, and humidity. Hence, the considered system is a strong candidate for use in the continuous monitoring of solar cell systems aiming to quickly intervene to solve any problems encountering operation, which is reflected positively on improving the solar system's performance. On the other hand, and based on the survey results of the solar irradiance profile, Luxor and Cairo cities are strongly candidated as suitable locations for solar power station installation.

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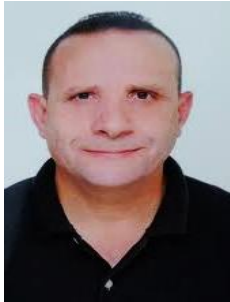
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