Proceedings of Engineering and Technology Innovation, vol. 21, 2022, pp. 10-19

A Solar Energy Harvester for a Wireless Sensor System toward Environmental Monitoring

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Received 01 January 2022; received in revised form 13 February 2022; accepted 14 February 2022

DOI: https://doi.org/10.46604/peti.2022.9210

Abstract

Harmful environments can cause severe health problems to individuals. Thus, this study proposes a solar-powered wireless sensor system to monitor the physical parameters of an ambient environment in real-time. This system is developed based on two sensors and a NodeMCU board that includes a microcontroller with a Wi-Fi chip. This system is built to measure the ambient temperature, relative humidity, atmospheric pressure, and ultraviolet (UV) index. The power supply of the system is a solar energy harvester, which consists of a solar cell, a DC-DC converter, and a rechargeable battery. This harvester is practically tested outdoors under direct sunlight. The proposed system experimentally consumes an average power of 40 mW over one hour, and the lifetime of this system is 123 hours in the active-sleep mode. The results demonstrate that the system can sustainably operate for monitoring the environmental data.

Keywords: wireless sensor system, environmental monitoring, solar energy harvester, rechargeable battery, Internet of things (IoT)

1. Introduction

In the last decade, wireless sensor systems had a robust effect in environmental monitoring applications [1-2]. These systems are extensively utilized to measure environmental parameters in real-time [3-6]. Batteries are often utilized to power the sensor systems, but they have a bounded lifetime [7-8]. Energy harvesting (EH) methods are utilized to extend the lifetime of the batteries [9-12]. These methods utilize various energy sources, e.g., solar [13], wind [14], thermal [15], mechanical [16], and radio frequency [17] sources. Solar energy is characterized by the higher power density compared to other energy sources [18]. However, the illumination rates of solar energy can change instantaneously. Therefore, energy-storage elements and DC-DC converters are needed to store and regulate the power extracted via EH methods. Two energy-storage elements, i.e., a super-capacitor and a rechargeable battery, are utilized as energy storage. Super-capacitors have lower energy densities than rechargeable batteries [19-20]. Thus, in this work, a battery is utilized. Moreover, a harvester utilizing solar energy is implemented to overcome the generic battery problem [21-26]. This proposed harvester grants the sensor system a more long-term lifetime.

In previous researches, different sensor systems were presented for environmental monitoring applications [27-30]. Senivasan et al. [27] implemented a harvester based on solar energy to power a wireless sensor network (WSN) mote, which included two NiMH batteries, a voltage regulator, and a temperature sensor. Its power consumption was 94.29 mW. Moreover, it had a lifespan of 38 hours, and the solar cell was large in the area. Chieng et al. [28] developed a sensor system that had a rechargeable battery with a capacitance of 1500 mAh. This system had a ZigBee module and a temperature sensor, consumed

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a high power of 91.41 mW, and worked for 40 hours. Joris et al. [29] introduced a sensor system that had a sigfox module and a SHT21 sensor. The supply was a 90 mAh battery. The system consumed the power of 107.7 mW, and its lifetime was 20 hours. Al Rasyid et al. [30] presented a sensor network that had a Zigbee module, a CO sensor, and a CO_2 sensor. The network consumed the power of 180 mW, and its lifetime was 50 hours.

This study proposes a self-sustainable wireless sensor system for the perpetual monitoring of environmental parameters. To monitor the parameters continuously, the lifetime of the proposed wireless sensor system should be prolonged. A low-power software algorithm is developed to increase the system lifetime until 123 hours, so the proposed system could work without replacing the battery. Additionally, the system is powered by a perpetual solar energy harvester to reach a higher lifetime. The harvester is developed based on a rechargeable battery that has high energy density. The system is implemented with the testing outdoors and consumes 40 mW. The sensor system measures four physical parameters: ambient temperature, relative humidity, atmospheric pressure, and ultraviolet (UV) index. The data of the system are gathered by two sensors, monitored on a serial monitor application, and sent to a cloud service via Wi-Fi. The primary contributions of the study are as follows.

(1) The study develops a self-powered wireless sensor system to continuously monitor the ambient temperature, atmospheric pressure, relative humidity, and UV index.

(2) The study designs a solar energy harvester to power the system with a solar cell and a rechargeable battery, saving the power consumption of the system with sleep commands and low-power hardware components.

The study is organized as follows. Section 2 reviews the works related to the architectures of sensor systems. Section 3 introduces the proposed architecture of the solar energy harvester and wireless sensor system. The hardware implementation of the proposed wireless sensor system with the harvester is described in section 4. The results are demonstrated in section 5 and discussed in section 6. The conclusion of the study is provided in section 7.

2. Related Works

Many wireless sensor systems utilized solar energy harvesters. For instance, Capella et al. [31] utilized a 5.4 cm × 4.2 cm photovoltaic panel, with a super-capacitor of 50 F and a battery together. The power system was sufficient to prolong the lifetime of the sensor system to one year. In the work of Alippi et al. [32], a maximum power point tracking (MPPT) circuit was proposed for a WSN. This circuit was low-cost and had small-size dimensions. The WSN monitored the luminosity of a marine system at various depths. It also measured the temperature of the system. A power management unit was operated with rechargeable batteries, which were realized to increase the lifetime.

In the work of Jang et al. [33], a WSN was proposed to monitor environmental data with different structures. It used a solar cell with 21 cm × 11.4 cm as well as the batteries which had a capacitance of 10,000 mAh for 8 nodes. The voltage of batteries was 4.15 V, and the voltage decreased when the solar cell did not charge the system. In the work of Ingelrest et al. [34] and Barrenetxea et al. [35], a WSN was presented to monitor harmful environments. A solar energy harvester was integrated per station to supply the sensor system, and a long-term system was deployed. The sensor system could last for 180 days. Lazarescu et al. [36] utilized a solar energy harvester in a gateway system because this gate consumed more power compared to the sensor system. The gateway was placed inside a birdhouse. The system was tested under direct sunlight, and the lithium-ion batteries could not be replaced due to the fixing place of the birdhouse.

3. Proposed Architecture

Fig. 1 demonstrates the proposed structure of the solar energy harvester as well as the wireless sensor system. The harvester includes a solar cell to detect the sunlight irradiance and a DC-DC converter to step up the solar cell output. A rechargeable battery is used as energy storage, and a NodeMCU board is used for processing the physical signals of two sensors (one for measuring the humidity, temperature, and pressure, and the other for sensing the UV index). Further, Wi-Fi is used to transmit the environmental data to a cloud service. Eventually, the environmental data of sensors are monitored on a serial monitor application. Fig. 2 illustrates the schematic diagram of the harvester with the sensor system. In this figure, the utilized solar cell is MPT 3.6-75 and is connected to the input of a LTC3105 DC-DC converter to charge a 18650 lithium-ion rechargeable battery. The used sensors are BME280 and GY1145, while the utilized NodeMCU board is Gizwits WiFi Witty ESP-12F.

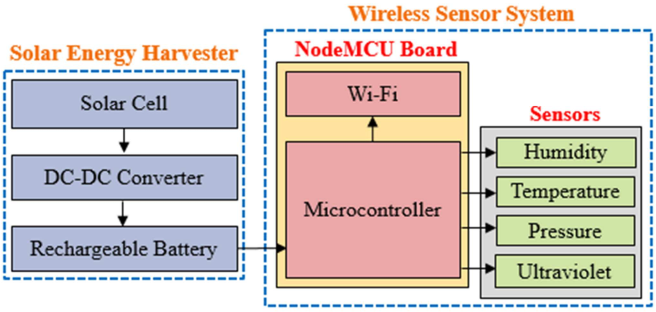

Fig. 1 The proposed structure of the solar energy harvester as well as the wireless sensor system

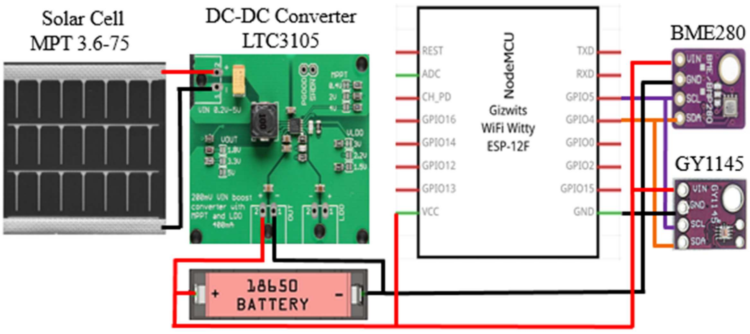

Fig. 2 The schematic diagram of the harvester with the sensor system

4. Implementation of the Wireless Sensor System

4.1. Hardware implementation

The setup of the wireless sensor system with the energy harvester is demonstrated in Fig. 3. It is implemented using the following hardware components: solar cell, DC-DC converter, rechargeable battery, BME280 sensor, GY1145 sensor, and NodeMCU board. Table 1 shows the characteristics of the used components in the wireless sensor system. The total cost of the proposed wireless sensor system is USD 120.

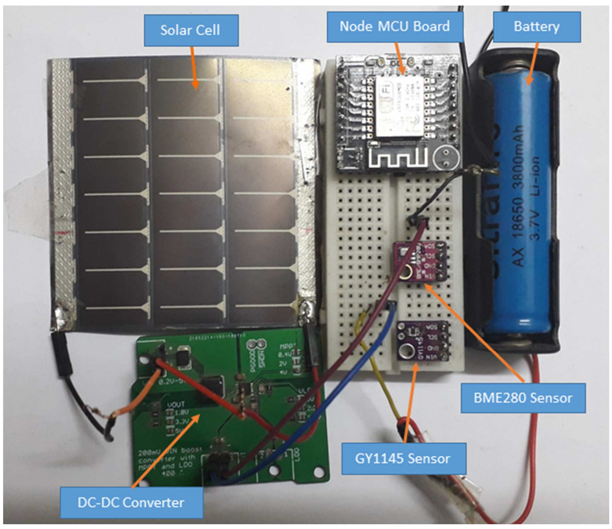

Fig. 3 The setup of the wireless sensor system with energy harvester

Table 1 Characteristics of the components used in the system

Component	Voltage	Current
BME280 sensor	3.3 V	3.6 μA
GY1145 sensor	3.3 V	1.4 μA
NodeMCU board	3.3 V	2.5 mA
Wi-Fi chip	3.3 V	70 mA

The system includes a low-power BME280 sensor, chosen from BOSCH® for sensing an environment's ambient temperature, relative humidity, and atmospheric pressure. This sensor draws a current of 3.6 μA and can sense the ambient temperature from -40 to 85°C, the relative humidity from 0 to 100%, and the atmospheric pressure from 300 to 1100 hPa. The GY1145 sensor measures the UV index and draws a current of 1.4 μA. The BME280 and GY1145 sensors are chosen because they are convenient for all environmental applications whether indoors or outdoors.

The brain of the system is a NodeMCU board from Espressif Systems®, which has small dimensions of 29.9 mm × 31.5 mm. Moreover, the NodeMCU board is utilized for processing the environment's data. The board consumes a low current of 2.5 mA, and 3.3 V is its operating voltage. The NodeMCU board is an open-source development board and has a built-in Wi-Fi chip. The Wi-Fi chip is used to transmit the data to a cloud service. This Wi-Fi chip has a range of 400 m and its current consumption is 70 mA. The NodeMCU board has a small size, but it consumes a high current due to its Wi-Fi chip. The NodeMCU board is chosen because it can be easily programmed with Arduino C language. In addition, this board is intended for Internet of things (IoT)-based applications. Therefore, the proposed wireless sensor system can be used in IoT applications.

The harvester contains a solar cell manufactured by Sundance Solar®. The dimensions of the solar cell are 7.2 cm × 6.0 cm. The cell is a thin-film and amorphous MPT 3.6-75 cell, and it gives the power of 180 mW at 1000 W/m^2 irradiance. The cell can convert light into electric power. The utilized solar cell has a maximum current and voltage of 50 mA and 3.6 V, respectively. Based on the calculations made, the MPT 3.6-75 cell is chosen.

The solar cell is connected in series to power a DC-DC converter, which is utilized to fix the solar cell output voltage. The converter is an LTC3105 converter. In other words, this converter charges one battery as a backup energy source. Therefore, this battery will have an overall capacitance of 3800 mAh and a voltage of 4.2 V, with an area of 11.7 cm^2. A MCP1700 low dropout voltage regulator is used to fix the battery voltage to 3.3 V because the NodeMCU board works at this value. The BME280 and GY1145 sensors, as well as the Wi-Fi chip, are fixed on the breadboard. This board has a total area of 3.0 cm × 7.0 cm.

4.2. Software implementation

The flowchart of the wireless sensor system is described in Fig. 4. It comprises sequential steps. The BME280 and GY1145 sensors are configured first, and then I^{2}C communication protocols are initialized for the mentioned sensors. Then, the initialization is carried out to the Wi-Fi, and the NodeMCU board is identified on the Ubidots platform. The NodeMCU board of the system works in two modes (active and sleep), so the sensor system works in the active mode. Then, the sensor system verifies the connection to the Wi-Fi network. If the status of the connection is equal to one, the NodeMCU board continuously reads the environmental data of the utilized sensors.

After the data is sent to the Ubidots platform for 10 seconds through the Wi-Fi, the sensors are turned off and the Wi-Fi goes into sleep. Then, the NodeMCU board is transferred into the sleep mode for a duration of 50 seconds. A serial monitor application is used for monitoring the data received from the system. In the active mode, the BME280 and GY1145 sensors are configured and I^{2}C protocols are initialized to these sensors. The NodeMCU board is also configured.

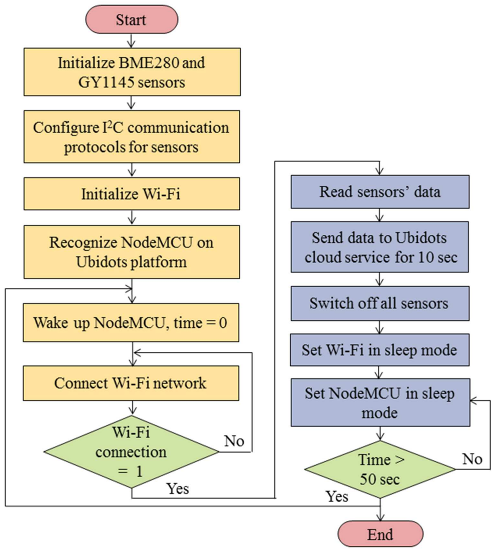

Fig. 4. The flowchart of the wireless sensor system

4.3. Wireless communication

The Wi-Fi chip type "ESP8266MOD" is utilized. The performance of the Wi-Fi chip depends on many factors, e.g., data rate, energy consumption, and security. The Wi-Fi has the power consumption of 70 mA at the active mode, and its data rate is 72.2 Mbps. The Wi-Fi is secure in transmission for certain data from one device to others. It provides multi security modes in data encryption and authentication. The operating frequency of the Wi-Fi is 2.4 GHz. It is a wireless protocol convenient for wireless systems.

In the proposed system, the utilized Wi-Fi is version 5.8, and it can save energy. The Wi-Fi is experimentally tested, and the measured current consumption is 0.2 mA at the sleep mode, showing that the Wi-Fi protocol is efficient. Moreover, the utilized Wi-Fi is suitable for EH systems and convenient with wireless systems including sensors. The Wi-Fi chip is compatible with ASCII commands, which are utilized in configuring communications. The utilized protocol in the Wi-Fi depends on the IEEE 802.11 b/g/n. Additionally, the data of utilized sensors connect to the NodeMCU board of the wireless sensor system through I^2C protocols.

5. Results

From the simulation of the solar energy harvester, Fig. 5 demonstrates the I-V characteristic curve of the solar cell under direct sunlight irradiance of 1000 W/m^2. The sunlight represents the source of illumination to validate the electrical characteristics of the utilized solar cell. It is clear that the maximum current of the solar cell is 50 mA at a voltage of 3.6 V. The output current and voltage values of the solar energy harvester are tested using two multimeters (one for the current and the other for the voltage).

Table 2 demonstrates the measured conversion efficiency of the solar energy harvester at various input power values. These values are measured at various irradiance levels of the sunlight using a solar power meter. These irradiance levels are 200, 400, 600, 800, and 1000 W/m^2, and the area of the solar harvester is 0.00432 m^2. Thus, the input power values to the solar harvester are 4319, 3446, 2588, 1730, and 859 mW with conversion efficiencies of 4.63, 3.47, 4.25, 2.89, and 2.91%, respectively. The corresponding output power values of the solar harvester are measured using two multimeters. It is clear that the maximum conversion efficiency (η) is 4.63%.

Fig. 6 illustrates the P-V characteristic curve of the solar cell under direct sunlight irradiance of 1000 W/m^2. This figure shows that the solar cell's maximum power (MPP) is 180 mW at 3.6 V. Practically, the voltage and current of the solar cell are measured via various resistors and 2 multi-meters (one multi-meter for measuring the current and the other for the voltage). The irradiance rate is measured on a sunny day, via a solar power meter.

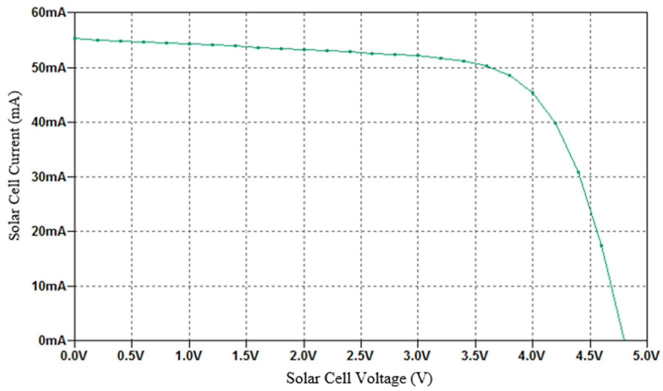

Fig. 5 I-V characteristic curve of the solar cell under 1000 W/m^2

Table 2 Conversion efficiency of the solar energy harvester

Output power (mW)	200	150	110	50	25
Input power (mW)	4319	3446	2588	1730	859
Conversion efficiency (η %)	4.63	3.47	4.25	2.89	2.91

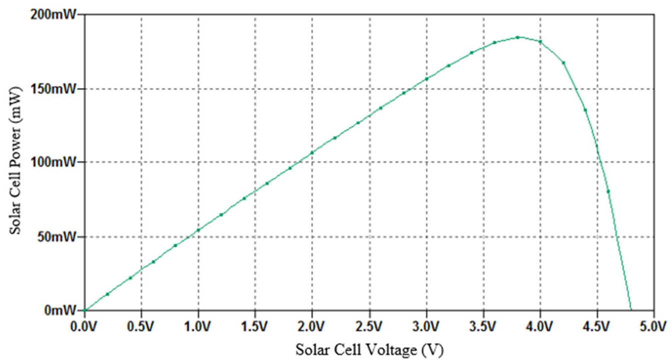

Fig. 6 P-V characteristic curve of the solar cell under 1000 W/m^2

Fig. 7 demonstrates the discharging curve of the 3800 mAh rechargeable battery for the system in the active-sleep mode. In this mode, the battery takes roughly 123 hours for discharging from 4.2 to 3.3 V, so the sensor system is powered without the harvester for 123 hours. The voltage of the battery stops at 3.3 V during the discharging operation because the NodeMCU board of the system works at this value. The system does not run if the voltage of the battery is less than 3.3 V. The voltage measurements for the battery are taken via a multi-meter.

Fig. 8 demonstrates the charging and discharging voltages from the solar cell and the battery over 539 hours. The charging experiment is executed outdoors with 1000 W/m^2 and is started at 12:00 pm on 11 June 2021 (sunny day). The discharging experiment is terminated after 539 hours. It is clear that the sensor system operates during different periods for discharging and charging the battery. The longest period for the wireless sensor system is tested to be 246 hours without being charged by the solar energy harvester. Eventually, the results demonstrate that the wireless sensor system is supplied using the solar energy harvester so that it can sustainably operate.

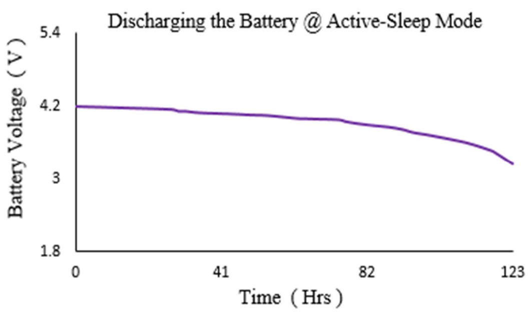

Fig. 7 The discharging curve of 3800 mAh battery

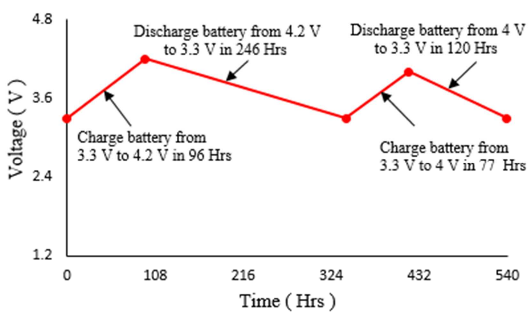

Fig. 8 The charging and discharging voltages for the battery during 539 hours

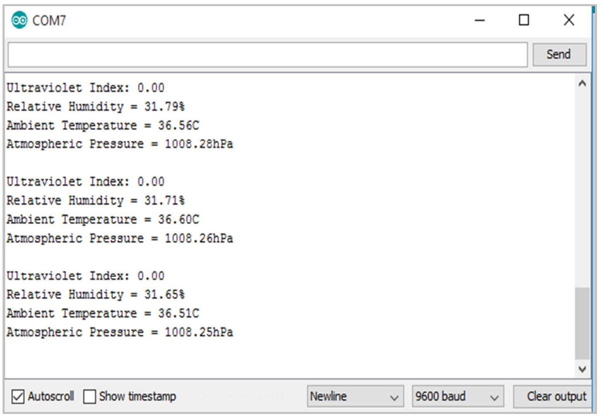

Fig. 9 A screenshot of the serial monitor application showing the monitored environmental data

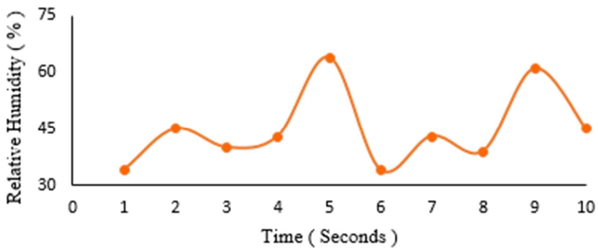

Fig. 10 Relative humidity measured by BME280

Fig. 9 reveals a screenshot of the displayed environmental data on a serial monitor application, which is conducted for monitoring the status of an ambient environment during the active period (600 seconds/hour) of the system. The monitored environmental data are instantaneously visualized on the application for every active period of the system. The environmental data (i.e., relative humidity, ambient temperature, atmospheric pressure, and UV index) can change continuously. At first, the UV index of the environment is shown to be 0.00, the relative humidity is 31.79%, the ambient temperature is monitored at 36.56°C, and the atmospheric pressure is 1008.28 hPa. Then, the UV index, relative humidity, ambient temperature, and atmospheric pressure are observed to be 0.00, 31.71%, 36.60°C, and 1008.26 hPa, respectively. From the serial monitor application, one can obtain the data of an ambient environment over time.

Fig. 10 demonstrates the relative humidity of an environment during the active time of BME280. The relative humidity is measured under various physical conditions of an environment. During the measurements, the wireless sensor system samples the BME280 sensor at a sampling rate of 100 Hz. It can be seen that the relative humidity continuously changes from 0 to 10 seconds and the maximum humidity percentage is 64. BME280 can sense the relative humidity from 0 to 100%. The humidity monitoring is achieved by the serial monitor application of Arduino, and then the results are saved in an Excel file.

6. Discussion

Table 3 illustrates the comparison of recent wireless sensor systems. In the proposed work, the developed system has 2 sensors (BME280 and GY1145), whereas the systems in [27-29] have only one sensor. The number of physical parameters of the proposed work is 4, while the system parameters in [27-29] are fewer. The Wi-Fi technology utilized in this study has a higher range than the technologies in [27-28]. Additionally, the lifetime of the proposed system is the longest compared to [26-28], and the power consumption of the proposed system is less than [27-29]. The proposed system consumes 40 mW. This value is achieved via the used microcontroller, sensors, and the developed algorithm. The microcontroller is operated in two modes (sleep and active), while the sensors are switched off sometimes to save power. Therefore, the proposed wireless sensor system has lower power consumption than [27-30], and the lifespan of the proposed work is longer than [27-30]. It can be seen that there is a trade-off among the type of energy storage, the amount of environmental data, the value of power consumption, and the type of the wireless technology chosen when developing the wireless sensor system in this study.

Table 3 Comparison of recent wireless sensor systems

Reference	[27]	[28]	[29]	[30]	The proposed work
Sensors	Temperature	Temperature	SHT21	TGS2442 for CO and TGS4161 for CO_2	BME280 and GY1145
Numbers of physical parameters	One	One	Two	Two	Four (relative humidity, ambient temperature, atmospheric pressure, and UV index)
Wireless technology	MICAz 2.4 GHz 75 m	Zigbee 2.4 GHz 100 m	Sigfox 2.4 GHz 10 km	Zigbee 2.4 GHz 100 m	Wi-Fi 2.4 GHz 400 m
Lifetime of system (Hrs)	38	40	20	50	Perpetual, and 123 without a harvester
Power consumption (mW)	94.29	91.41	107.7	180	40

7. Conclusions

This study introduces a perpetual solar energy harvester to supply a wireless sensor system for environmental monitoring. The solar energy harvester is designed to increase the lifetime of the wireless sensor system from 2 to 123 hours. The power consumption of the system is 40 mW. The sensors' data of the system are instantaneously monitored on the serial monitor application. The system is tested experimentally to measure the physical parameters (i.e., ambient temperature, relative humidity, atmospheric pressure, and UV index) of an ambient environment in a continuous mode. Finally, the designed solar energy harvester enables the sustainable operation of the proposed monitoring system in sunny environments.

In the future, the author will consider a battery that has a capacity higher than 3800 mAh. Further, the power performance of the solar cell will be tested at different bending angles. The testing of the cell is important to verify the sustainability of the solar energy harvester. Additionally, the product of the wireless sensor system could be manufactured using a printed circuit board. One could apply the wireless sensor system for pollution monitoring. Also, one could use the sensors under humid environments, e.g., precipitation.

Conflicts of interest

The author declares no conflict of interest.

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