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Research Article

Design, Fabrication, and Experimental Study of a Low-cost and Accurate Weather Station Using a Microcontroller System

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ABSTRACT

In this research study, a cost-effective and reliable weather station using a microcontroller system containing instruments and sensors for measuring and recording ambient variables was designed, fabricated, and tested. The dataset recorded and stored in the meteorological system can be applied to conduct various research in the field of energy and environment, especially in solar systems. Employing a microcontroller system reduces costs and provides special features such as accessing data on the web-based spreadsheets and adding control devices. In this system, meteorological information including solar radiation, air temperature, wind velocity, and air relative humidity is measured and saved in user-defined time intervals such as 30 seconds. The total cost for measuring equipment, sensors, and microcontroller along with a data logger is about 110 USD. To demonstrate the importance of using local meteorological data, in the vicinity of the case studies, the dataset provided by the local weather station was compared with the meteorological data of two nearby national stations for one month. The results revealed that the values reported by the national stations were different from the actual values measured by the local weather station. The deviations for solar radiation, wind velocity, air temperature and humidity values were at least 5, 9, 7%, and more than 100%, respectively.

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1. INTRODUCTION

Accurate weather data availability is vital for conducting research in the field of energy and environment and analyzing the performance of energy systems, especially renewable systems (Duffie and Beckman, 2013). For instance, one of the most significant factors in measuring the performance of a solar system is monitoring of both operating parameters and weather conditions. Also, development of energy performance indicators and energy baselines for energy management purposes requires historical data including meteorological variables (Moghadasi et al., 2021). In this regard, in most studies, national meteorological data have been applied to analyze the performance of these systems. The use of this meteorological information may cause errors in performance analysis due to possible differences between national and local data. Hence, the local weather measurements can enhance energy performance analysis. In the past, all systems for measuring ambient variables such as temperature, humidity, and wind velocity worked mechanically. Therefore, to record them, the only method was to read and record the measures manually in the specified time intervals. In previous years, by developing semiconductors, electronic circuits were used to measure meteorological parameters and display and record them digitally. The advantages of digital systems include high accuracy, fast response, automatic operation, small dimensions, long life cycles, and low price (Rafiquzzaman, 2014). In this regard, Pashchenko and Rassadin developed a microclimate weather station containing wireless sensors, a data collector, and an analytical tool in 2022. This system was part of a project to model building energy consumption. Data were collected from temperature, humidity, CO_2 concentration, and light intensity parameters in the location inside the studied building in Moscow city for the period of the Coronavirus quarantine lockdown. TD-11, Vega Smart-UM0101, ERS, and ERS CO_2 sensors were used to measure environmental parameters and the ELT-2 sensor was utilized for connecting through the LoRaWAN protocol (Pashchenko and Rassadin, 2022). Monteiro et al. built a microclimate weather station on the university campus in 2019. This research focuses on the development of a wireless network of ambient monitoring stations utilizing IoT technology to provide users with weather data for daily planning purposes. DSM501A sensor was used in the proposed device to monitor air pollution. Also, the parameters of CO, CO_2, temperature, humidity, and air pressure were measured by the system (Monteiro et al., 2019). Wang et al. investigated the performance of a microclimate monitoring system located on the SouthEast University campus with the help of long-term data from the urban weather station and EnergyPlus software tools. The results indicated that there was a significant difference between the three datasets. For example, the mean air temperatures in the microclimate station

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were 1.2 and 2.2 ºC higher than the city climate station and EPW data (Wang et al., 2021). Moreover, Cureau et al. (2022) presented a wearable mobile system to monitor environmental parameters. BME280 sensor was used to measure the parameters of ambient temperature, humidity, and pressure, while the CV7-V sensor to measure the parameters of wind velocity and wind direction. Also, SP-510-SS, SE-421, TDS0037, PMS5003, OX-A431, NO_2-A43F, and NEO-M8 sensors were utilized to measure the parameters of solar irradiance, illuminance, CO_2 concentration, particulate matter concentrations, O_3 concentration, NO_2 concentration, and GPS unit, respectively. This system included the sensors connected to a control system that was portable and could be connected to other devices via Wi-Fi. By validating the data, it was concluded that the highest and lowest rates of measurement accuracy were assigned to the ambient temperature values and CO_2 concentration parameters with root mean square error equal to 0.46% and 49.42%, respectively (Cureau, Pigliautile and Pisello, 2022). Moghadasi et al. conducted an experimental study on a solar air heater with a specific geometry with access to data collected by a microclimate weather station, which was built and deployed at the data collection site. The parameters such as inlet and outlet temperature, radiation, wind velocity, ambient air temperature, and humidity were measured by the DS18S20, BH1750FVI, AM2302, and 652-1010 Robinson Cup type sensors, respectively (Moghadasi et al., 2022). Besides, this group used the weather station data in the development of machine learning prediction models for the purpose of optimal operation of the mentioned air heater (Moghadasi et al., 2023). Abbate et al. installed an automatic weather station connected to the network in the Alpine glacier (harsh weather conditions) in the north of Italy in 2013 (Abbate et al., 2013). Nsabagwaa et al. proposed an automatic weather station system at a low price in Uganda. The total cost of the proposed system was significantly cheaper than conventional types. The cost of the provided system was calculated as 1800 USD, while the price of conventional automatic weather station commercial data collection systems reached 7000 USD (Nsabagwa et al., 2019). In 2019, Netto and Neto designed an open-source automatic weather station to measure the effects of climate change on glaciers. They utilized a set of low-cost sensors, all of which were customized for use in natural glacier environment conditions (Netto and Arigony-Neto, 2019). Bernardes et al. (2022) introduced an affordable automatic weather station system using Commercial Off-The-Shelf and IoT technologies. A photovoltaic panel was applied to feed the system. An intelligent sensor calibration method was proposed to improve reliability (Bernardes et al., 2022).

Table 1. Detailed description of related works.

Author(s) / year	Collected parameters	Related accuracy	Main purpose of system development	Cost (USD)
Pashchenko and Rassadin / 2022	Temperature, humidity, CO_2 concentration, and light intensity	-	Building energy consumption modeling	-
Monteiro et al. / 2019	CO concentration, temperature, humidity, air pressure, and CO_2 concentration	-	Microclimate monitoring of a university campus using IoT	-
Wang et al. / 2021	Temperature, humidity, wind speed, and solar radiation	Temperature: ±0.21, humidity: ±2.5%, wind speed: ±4%, wind direction: ±5°, solar radiation: ±5%	Comparing local weather stations with meteorological and use in energy simulation	-
Cureau et al. / 2022	ambient temperature, humidity and pressure, wind velocity, wind direction, solar irradiance, illuminance, CO_2 concentration, particulate matter concentration, O_3 concentration, NO_2 concentration	Air temperature: ±1 °C, humidity: ±3%, atmospheric pressure: ±0.25%, wind direction: ±1°, solar radiation: ±5%, illuminance: ±5%, CO_2 concentration: ±2%,	Monitoring hyper-microclimate	-
Moghadasi et al. / 2022	Inlet and outlet air temperatures, radiation, wind velocity, ambient air temperature and humidity	Temperature: ±0.5°C, humidity: ±2%, solar radiation: ±2%, wind velocity: ±1%	Fabrication and testing of a new solar air heater – current present	110
Abbate et al. / 2013	Wind speed and direction, Snow height, Solar radiation, Air temp, and relative humidity	-	Installing an automatic weather station on a glacier	-
Nsabagwaa et al. / 2019	Temperature, Soil Moisture, Humidity, Wind Speed, Wind Direction, Solar Insolation, and atmospheric pressure	±0.5	Toward a robust and affordable Automatic Weather Station	1800
Netto and Neto / 2019	Atmospheric pressure, Humidity, Solar radiation, Temperature, Wind velocity, and direction	-	Investigation of effects of climate change on glaciers	202
Bernardes et al. / 2022	Wind speed and direction, Rain gauge, Temperature, pressure, and humidity	-	Natural disaster monitoring	-

According to the literature review, the high total cost of implementing local weather stations is one of the main factors that must be taken into account when considering the utilization of this system in the case study area. To solve this issue, in this research, a cost-effective weather station was designed, fabricated, and tested. The main features and advantages of the proposed system include (a) high accuracy, (b) low cost, (c) using a microcontroller system for recording and storing data, and (d) online monitoring using IoT.

2. MATERIALS AND METHODS

2.1. General Components of a Weather Station

In the analysis of the energy and environment systems, the most important meteorological parameters are solar irradiance, air temperature, wind speed, and relative humidity. In this sub-section, brief descriptions are provided in connection with common measuring equipment for monitoring these parameters.

2.1.1. Wind Speed

Anemometer instrument is employed to measure wind speed. The anemometers are divided into two categories according to the type of performance: (a) the first group measures the wind speed and (b) the other group measures wind pressure. Since the speed and pressure of the wind are related, the other can be calculated by measuring each of these two quantities. Conventional anemometers are:

(A) Cup anemometer: It is one of the most used types of anemometers. This speedometer usually has three cups at an angle of 120 degrees. The material of this blade differs from those in various models and it has several types of fiberglass, iron, aluminum, or plastic. These sensors measure the wind speed by detecting the rotation of the blade and counting the angular speed of the blade (Baseer et al., 2016).

(B) Vane anemometer: It has a propeller parallel to the vertical axis, which is connected to the speedometer. In this type, the rotation speed of the blades is converted into the equivalent wind speed and shown on the display (Pham, 2014).

(C) Ultrasonic anemometer: In this anemometer, two or three sound receivers are installed on the bowls at a perpendicular angle to each other. The electronic circuits inside the anemometer measure the difference between the round trip of the sound and convert it into the equivalent wind speed (Mustafa et al., 2016).

(D) Hot wire anemometer: In this type, the wind changes the temperature of the hot wire and the wind velocity is measured by the electric current required to keep the wire warm and exposed to the wind at a constant temperature. Figure 1 shows the types of anemometers (Ligęza, 2009).

a b c d

Figure 1. Types of Anemometer: (a) cup, (b) vane, (c) ultrasonic, (d) hot-wire.

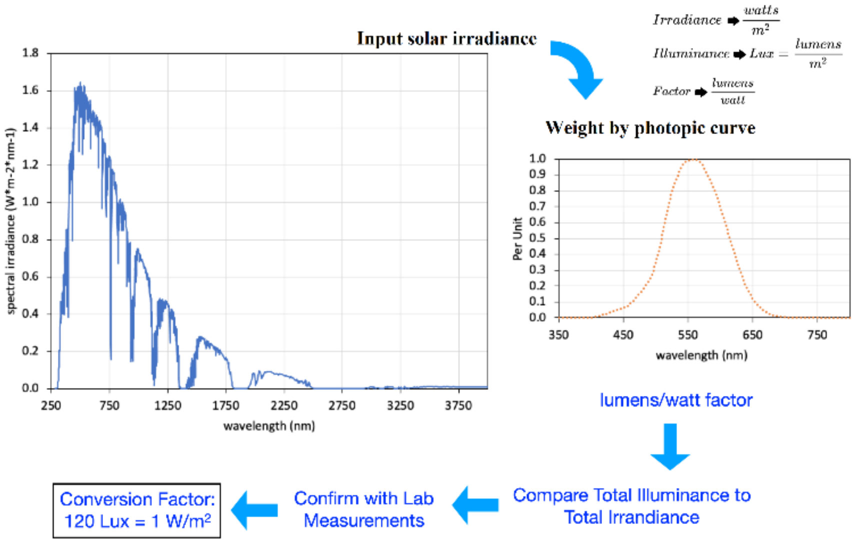


Figure 2. Stages of converting the ambient light into solar irradiance (Michael and Moreno, 2020).

2.1.2. Solar Irradiance

One of the most important meteorological parameters is solar irradiance. Pyranometers are generally employed to measure solar irradiance since they are the most accurate sensors to collect this parameter (Blum et al., 2022). Nevertheless, pyranometers are costly and their deployment throughout the territory, whether on local weather stations or specific locations, is not economically feasible. A simple and low-cost alternative way is to measure the ambient light and calculate the irradiance based on it, which is applied in this work. In 2020, Michael et al. presented a way to convert the ambient light into the amount of solar irradiance based on Figure 2. They measured ambient light and irradiance in different conditions and by comparing them, they found a linear relationship between them (Michael and Moreno, 2020).

As the main outcome, the measurement and analysis of modeling results proved that 120 lx of illumination was equal to 1 watt per square meter of solar irradiance.

2.1.3. Relative Humidity

It is possible to measure the relative humidity of the air directly with different sensors. DHT series sensors are often used in microcontroller systems. Among the features of these sensors are small size, low price, and high accuracy. In this type, relative humidity values are sent directly to the microcontroller (DHT22 technical details, 2023).

2.1.4. Air Temperature

There are different sensors to measure air temperature. The conventional and widely used sensor is a K-type thermocouple for measuring temperature. This sensor converts temperature into voltage and the microcontroller reports the measured temperature by converting this voltage into temperature (Radajewski, Decker and Krüger, 2019). The utilization of this sensor is constrained by limitations such as the length of the wire, the inability to add a wire to the sensor, and the need for regular calibration of the data logger. Another type is the digital temperature sensor that reports the temperature directly to the microcontroller and does not have the above limitations.

2.2. Design and Fabrication of the Proposed Weather Station

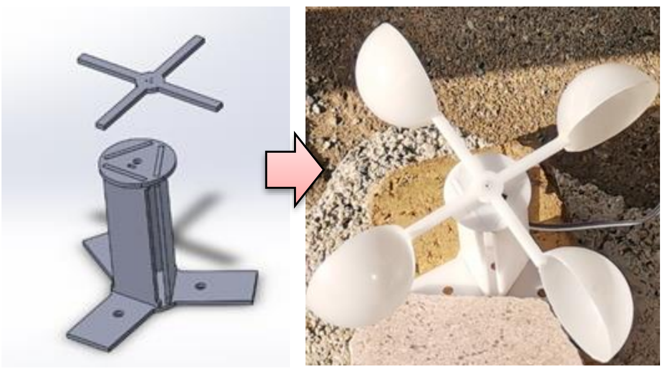
To use meteorological data in the analysis of the energy and environmental systems, especially solar systems, the range of changes in weather parameters have been considered according to Table 2 in the design and fabrication of the local weather station, in addition to the techno-economic criteria.

Table 2. The range of weather parameters values.

No.	Parameter	Most common natural range	Unit
1	Irradiance	0 to 1300	$W.m^{-2}$
2	Wind speed	0 to 30	$m.s^{-1}$
3	Air temperature	(-10) to (+50)	°C
4	Air humidity	10 to 100	%

2.2.1. Anemometer

By comparing four anemometer models, introduced in Subsection 2.1.1, the vane anemometer has the lowest price. Of note, this sensor must be placed perpendicular to the wind flow to measure the airspeed. Therefore, this anemometer is not suitable for continuous monitoring of the ambient wind velocity. Hence, the most suitable and economical sensor to measure this parameter is the cup anemometer. In this research, according to Figure 3a, the anemometer parts are designed by SolidWorks software (Bai et al., 2021) and made by laser cutting from the Plexiglas board following the reference sizes. Finally, they are connected together with the cups. The built anemometer is illustrated in Figure 3b.



(a) (b)

Figure 3. (a) Anemometer design in SolidWorks software and (b) built anemometer.

In this anemometer, a low-mass magnet is attached to the vane. A pulse is sent to the microcontroller after each time the magnet passes in front of the Hall-effect sensor, which is installed on the body of the anemometer. In the microcontroller, the rotational speed of the anemometer is computed by calculating the time between the pulses. The wind speed calculation is as follows (Anemometer Instructions, 2005):

1- Determining the radius of rotation (*r*) by measuring the distance from the center of the cup to the center of rotation;
2- Obtaining the number of revolutions of the anemometer in one minute (*n*);
3- When one of the cups travels a full circle, it travels a distance equal to the circumference of the circle (*S*), which is calculated by Equation 1;

$$S = 2 \times \pi \times r \quad (1)$$

4- In the last step, the average wind speed (*v*) is calculated based on Equation 2 in one minute.

$$v\ (^{m}/_{s}) = \frac{n \times S}{60} \quad (2)$$

2.2.2. Digital Ambient Light Sensor

In this research, the ambient light was measured using the BH1750 sensor (refer to Figure 4.a). Then, the amount of irradiance was calculated using the linear relationship (120 lx of illumination = 1 $\frac{W}{m^2}$ of solar irradiance) (Michael and Moreno, 2020). The important specifications of the BH1750 (ROHM semiconductor Instructions, 2023) are as follows:

- Illuminance to digital converter,
- Wide range,
- Low current,
- Light noise reject function,
- 1.8V logic input interface, and
- Adjustable measurement result for the impact of optical windows.

2.2.3. Digital-output Relative Humidity Sensor

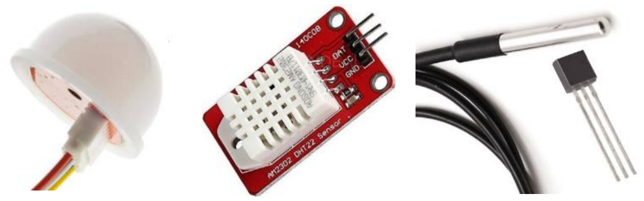
Air humidity is directly measured by the sensor DHT22 (refer to Figure 4.b). The main specifications of this sensor are (DHT22 technical specifications, 2023):

- 3.3 V to 6 V DC,
- Digital signal via single-bus,
- Accuracy: ±2%,
- Resolution or sensitivity: 0.1%,
- Repeatability humidity: ±1%,
- Long-term stability,
- Sensing period average: two seconds, and
- Fully interchangeable property.

2.2.4. Digital-output Relative Humidity Sensor

One of the most common sensors is the DS18B20 temperature sensor (Figure 4.c), which is used in this research. This sensor measures the temperature with an accuracy rate of 0.5 °C. This sensor is advantageous as it does not require periodic calibration and has a low price, high accuracy, and suitability for long wire lengths. It also features a digital output that enables parallel connections of multiple sensors. Furthermore, the information transmitted by the sensors has a specific address, which can be separated in the microcontroller. The important specifications of the DS18B20 (DS18B20 technical details, 2023) are as follows:

- Multidrop capability,
- 3 – 5.5 V,
- Measuring range: -55 °C to +125 °C,
- ±0.5 °C accuracy,
- Wide applications in various systems.



a b c

Figure 4. (a) light sensor, (b) relative humidity sensor, (c) temperature sensor

3. EXPERIMENTAL SETUP

The proposed weather station consists of two main parts: (a) equipment for measuring environmental parameters and (b) a data logger. Environmental variables are measured by installing sensors of the anemometer, illuminance meter, ambient temperature, and relative humidity on special bases, as shown in Figure 5. In this regard, several considerations must be taken into account: (a) The anemometer should be placed away from any surfaces to avoid interference and ensure collection of data specific to the surrounding area. (b) The illuminance sensor (type BH1750) should be covered with a waterproof cover and installed in a location where it will not be affected by shadows during any time of day. (c) The temperature sensor (type DS18B20) is coated with waterproof steel and should not be exposed to direct sunlight. (d) The relative humidity sensor (Type DHT22) should be protected from sunlight and rain during installation.

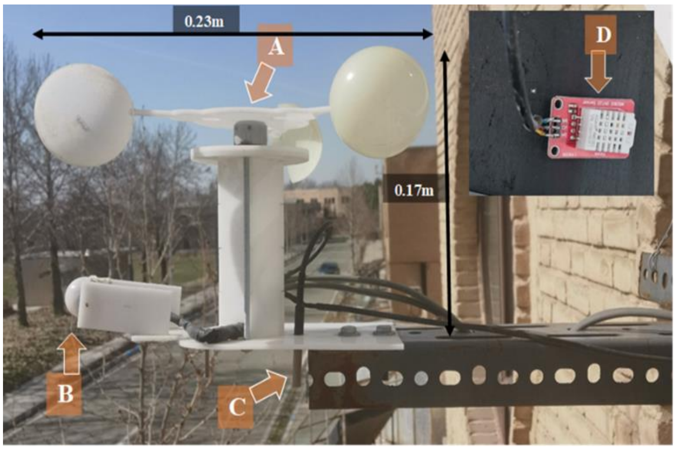


Figure 5. View of the proposed weather station and dimensions: (A) anemometer, (B) illuminance sensor with waterproof cover, (C) waterproof air temperature sensor, and (D) relative humidity sensor (installed on the backside of the device)

Based on Figure 6, monitoring and recording the measured data require a system consisting of a microcontroller, power supply, display screen, clock module, and SD memory card. This system has the ability to connect to the Wi-Fi network and can save the data locally (offline). Also, the data can be saved online (on the Google Sheets platform). The possibility of connecting to the network provides the ability to view real-time data, in addition to storing data and accessing them through the Internet.

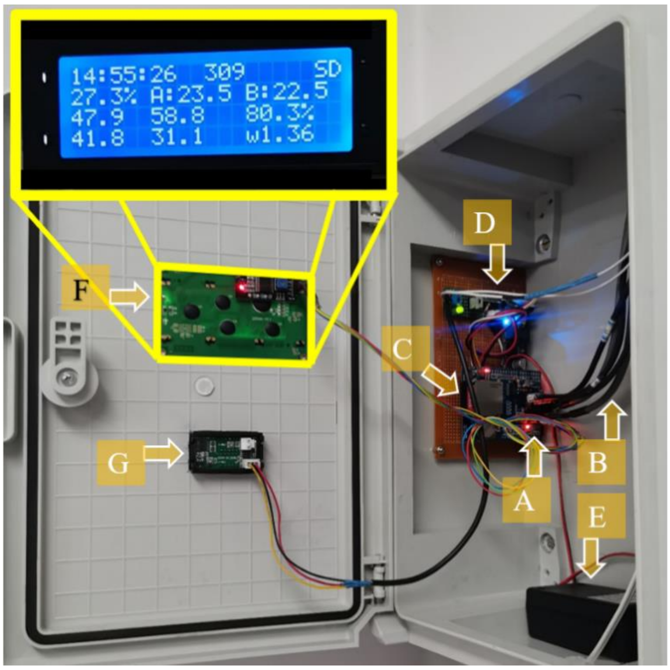


Figure 6. The data logger and components: (A) Wi-Fi-based microcontroller and datalogger module, (B) sensors wires, (C) SD card slot, (D) power module (voltage regulators), (E) power supply, (F) main screen, (G) second screen.

3.1. Weather Station Total Cost

One of the main advantages of the proposed meteorological station is the low total cost, which makes it affordable for wide applications such as performance analysis of energy and environmental systems. The total cost of building this station is about 110 USD and the relevant details are presented in Table 3.

Table 3. Details of the weather station components' price

No.	Item	Price (USD)
1	Air temperature sensor	5
2	Air humidity sensor	7
3	Anemometer	22
4	Illumination sensor	4
5	Microcontroller	7
6	Datalogger module (time and SD card module)	17
7	Power supply and voltage regulators	10
8	Display module	13
9	Structure, wiring, etc.	25
	Total cost is equal to:	**110 USD**

4. RESULTS AND DISCUSSION

4.1. Measurement Results

The ambient variables were experimentally measured in the winter of 2022 in the city of Karaj, Iran, at the location coordinates of 35°74′00” N, 50°95′00” E. Figure 7 showcases an instance of the measured data trend for three days.

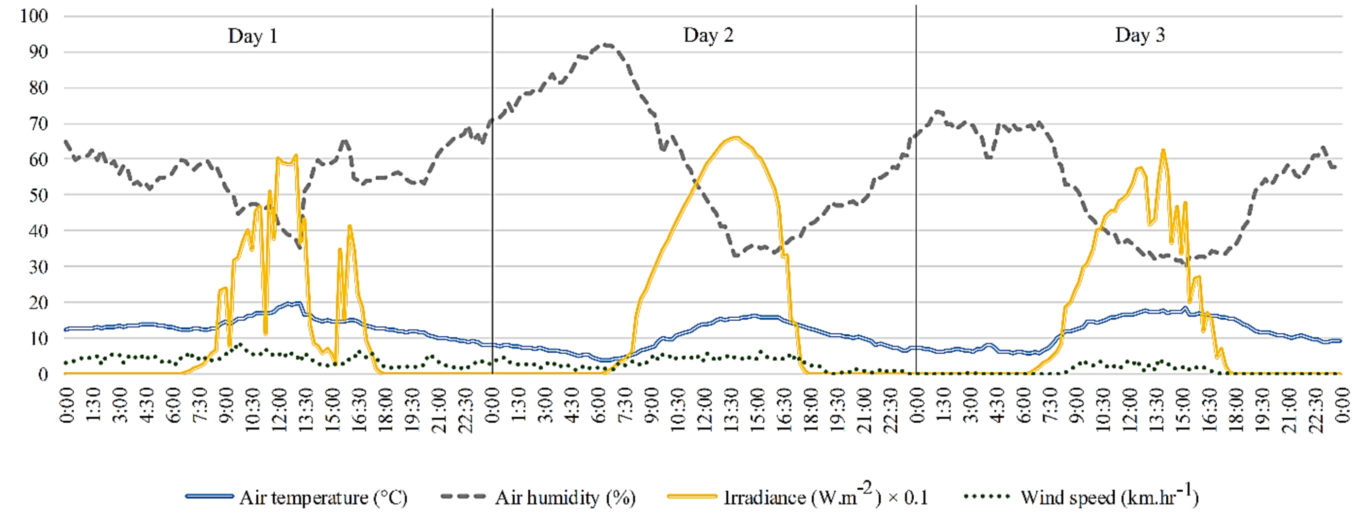


Figure 7. Trends of sample ambient parameters values.

Average data in 15-minute periods are plotted in Figure 7. As mentioned, one of the important advantages of the proposed weather station is access to real-time data on the Internet. Figure 8 illustrates a sample of an online data display.

4.2. Comparison of The Proposed Weather Station Data with National Meteorological Data

Most of the related studies have applied national meteorological data to analyze the performance of energy and environmental systems. Due to the difference in data, using this national meteorological information may cause errors in the performance analysis of the mentioned systems. In order to investigate this difference, the data recorded from the local station were compared with the data from two stations nearby the experiment site in November 2022. According to Figure 9, the closest national stations are the Alborz meteorological station with a distance of 4 km and the Chitgar meteorological station with a distance of 19 km. In addition, the geographical locations of stations are presented in Table 4.

Table 4. Geographical location of stations.

Location	Longitude (°)	Latitude (°)	Altitude above sea level (m)
Local Station	50.9575	35.7486	1248
Alborz Station	50.9395	35.7814	1263
Chitgar Station	51.1723	35.7492	1314

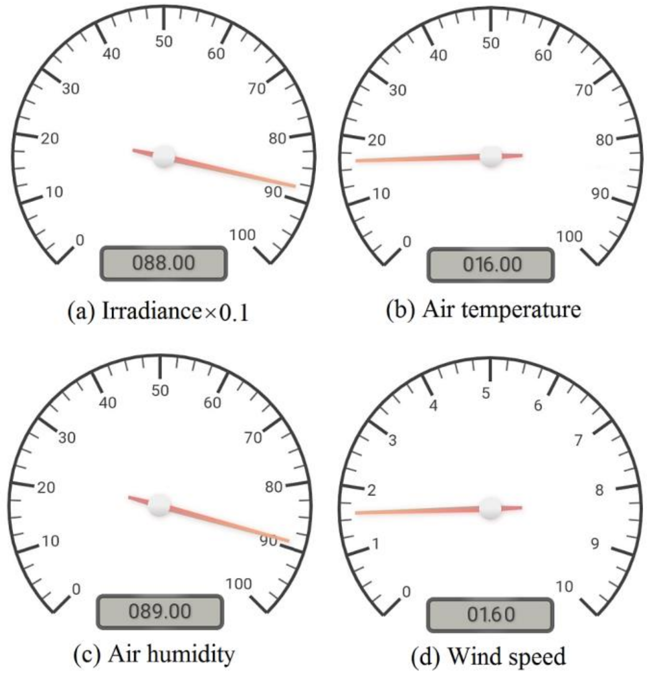


Figure 8. Online real-time data visualization

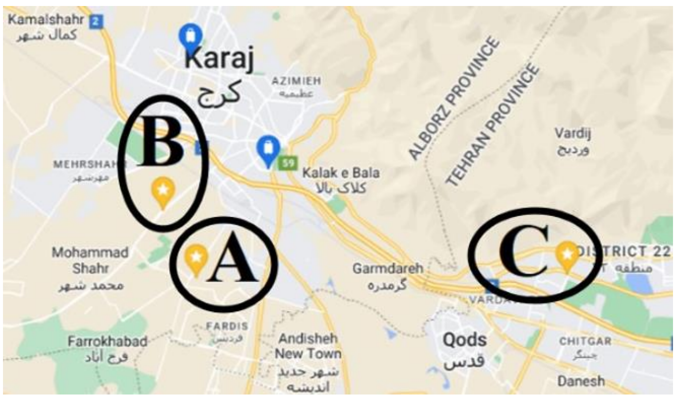


Figure 9. (A) The location of the proposed weather station, (B) Alborz meteorology office, and (C) Chitgar weather station

Daily average values were used to compare the data. Figure 10 shows the average daily air temperature in November.

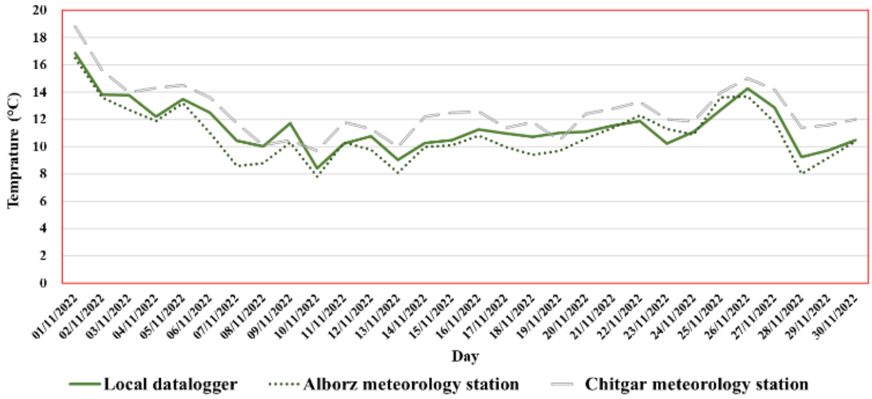


Figure 10. Daily average values of air temperature were reported by the weather stations

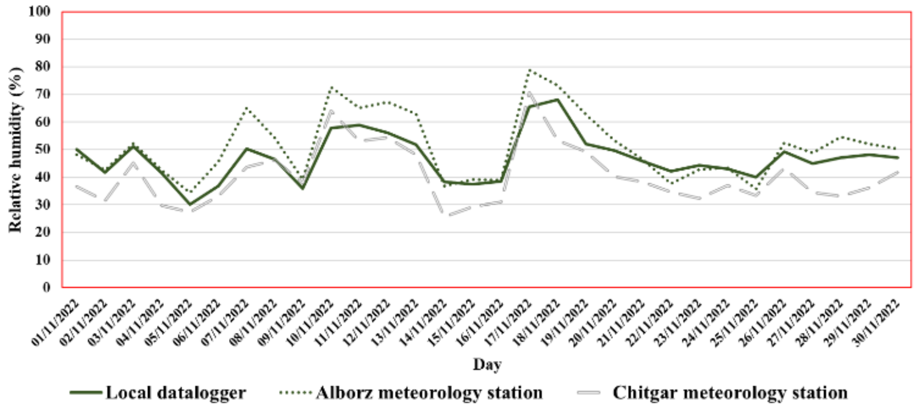


Figure 11. Daily average values of air relative humidity recorded by the weather stations

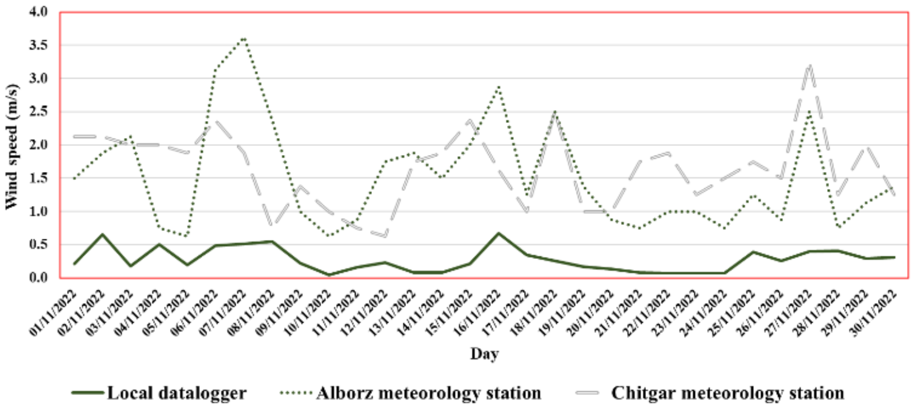


Figure 12. Daily average values of wind speed recorded by three weather stations

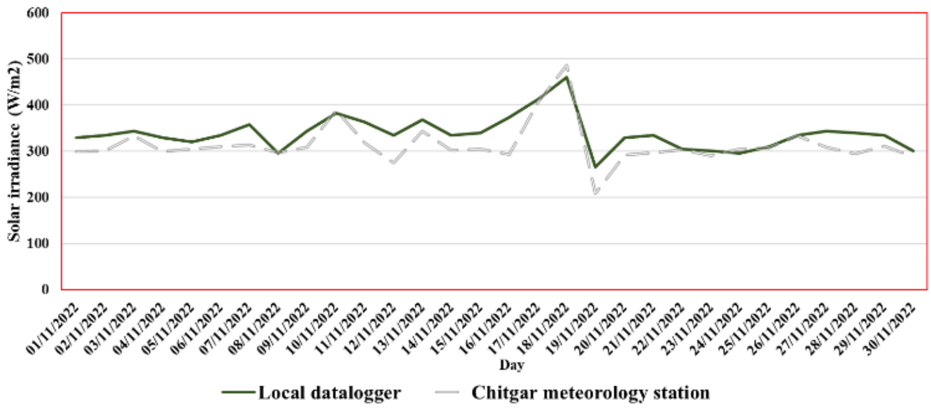


Figure 13. Daily average values of solar radiation reported by the weather stations

According to Figure 10, the trends of air temperature data are similar. Alborz station has recorded closer to the real world values than Chitgar station due to its proximity to the local station. The monthly average deviation of the local data from the Alborz station is 0.6°C (5%), and from the Chitgar station is 1.1°C (10%). Figure 11 displays the trend of air relative humidity in November.

Based on Figure 11, it can be observed that the average monthly difference in relative humidity between the local weather station and the Alborz weather station is 4.3% (9%), while it is 6.5% (14%) with the Chitgar weather station. Average daily wind speed values are presented in Figure 12.

The values of wind speed in 3 weather stations are very different, as shown in Figure 12. This issue results from the existence of the building at the location of the local station, the various urban structures, and also the relatively long distance between the stations**.** The average monthly difference in local wind velocity is 1.6 m/s (456% difference) compared to the Alborz weather station, and 1.4 m/s (498% difference) compared to the Chitgar weather station, as shown in Figure 12. Therefore, it is not practical to use this data. Finally, the average daily solar irradiance data sets are shown in Figure 13.

Alborz meteorological station measures and reports the values of wind velocity, ambient temperature, and humidity. Chitgar meteorological station also measures and reports solar irradiance, in addition to the three mentioned parameters. According to Figure 13, the average data difference in November at two local weather stations and Chitgar is 24 W/m^2 (7%). To review the measurement results, the lowest, highest, and average values of the meteorological variables are presented in Table 5.

Table 5. The range of daily data in November 2022.

Parameter (Unit)	Local station			Alborz station			Chitgar station		
	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
Air temp (°C)	8.44	16.86	11.45	7.80	16.50	10.86	9.70	18.8	12.58
Humidity (%)	30.1	68.0	47.0	34.5	78.9	51.3	25.6	70.8	40.5
Wind velocity ($m.s^{-1}$)	0.05	0.67	0.28	0.63	3.63	1.53	0.63	3.25	1.65
Solar irradiance ($W.m^{-2}$)	267	461	339	N/A	N/A	N/A	209	487	315

5. CONCLUSIONS

For analyzing the performance of energy and environmental systems, especially solar energy, the most important environmental parameters to consider are solar radiation, wind velocity, ambient temperature, and humidity. In this research, a weather station was designed, built, and tested to measure the above parameters at the data collection site. The important features of this weather station were portability, acceptable accuracy, and low cost (110 USD). This system contained two important parts including environmental measurement sensors and a data logger. By using the data logger, the meteorological data were stored online and offline at the specified time interval. By comparing the local station data with the national stations in November 2022, the following results are obtained:

- The average monthly difference between the local air temperature data and the Alborz station is 5%, and with the Chitgar station, it is 10%.
- The average monthly difference in relative humidity between the proposed weather station and the Alborz meteorological station is 9%, and 14% with the Chitgar station.
- The average monthly difference in local wind velocity data compared to Alborz and Chitgar meteorological stations is 1.6 m/s (456% difference) and 1.4 m/s (498% difference), respectively.
- The average monthly difference in irradiance data between the proposed local meteorological stations and the Chitgar station is 24 $W.m^{-2}$, equivalent to a 7% difference.

For future research, we recommend using new modeling methods with artificial intelligence and machine learning to predict environmental parameters. Also, the ambient data of the meteorological station will be used for the optimal operation of solar systems such as solar water heaters and solar air heaters.

6. ACKNOWLEDGEMENT

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NOMENCLATURE

IoT	Internet of things
n	Number of revolutions of the anemometer in one minute
S	Circle circumference (m)
r	Radius (m)
v	Wind speed ($m.s^{-1}$)

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