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Low cost climate station for smart agriculture applications with photovoltaic energy and wireless communication

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A R T I C L E I N F O

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A B S T R A C T

Measuring climatic conditions is a fundamental task for a wide array of scientific and practical fields. Weather variables change depending on position and time, especially in tropical zones without seasons. Additionally, the increasing development of precision or smart agriculture makes it necessary to improve the measurement systems while widely distributing them at the location of crops. For these reasons, in this work, the design, construction and fabrication of an adaptable autonomous solar-powered climatic station with wireless 3G or WiFi communication is presented. The station measures relative humidity, temperature, atmospheric pressure, precipitation, wind speed, and light radiation. In addition, the system monitors the charge state of the main battery and the energy generated by the photovoltaic module to act as a reference cell for solar energy generation capability and agrivoltaic potential in the installation area. The station can be remotely controlled and reconfigured. The collected data from all sensors can be uploaded to the cloud in real-time. This initiative aims at enhancing the development of free and open source hardware that can be used by the agricultural sector and that allows professionals in the area to improve harvest yield and production conditions.

Specifications table:

Hardware name	Open source solar-powered wireless weather station
Subject area	• Engineering • Instrumentation • Internet of things
Hardware type	• Measuring physical properties and in-lab sensors • Field measurements and sensors • Electrical engineering and computer science
Open source license	Creative Commons Attribution-ShareAlike license
Cost of hardware	USD 512 (WiFi communication) - USD 565 (3G communication)
Source file repository	https://doi.org/10.17605/OSF.IO/NTVXG

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1. Hardware in context

Climate change and meteorological conditions research have been of great importance in the evolution of humanity, since it allows us to predict risks in different fields such as aviation, agronomy, construction, medicine, among others [1–5]. In addition, measuring climatic variables is a fundamental task for ecosystem characterization [6], development of smart and precision agriculture [1], solar photovoltaic (PV) system characterization [7] as well as combinations of the latter two: agrivoltaic system monitoring [8,9]. The numerous applications of such measurements have encouraged the development of both commercial systems as well as open source prototypes comprised of low-cost or own-made sensors interconnected and deployed with wireless communication networks. This in turn enables real-time information acquisition and developing processing and visualization platforms that facilitate understanding the data in the context of the applications.

Many different companies have developed commercial climate station systems, however, the cost is high (e.g. popular brands such as Vantage Pro and Libelium have basic stations costing $ USD and €7350 respectively [10,11]). In addition, the flexibility of commercial systems is limited to specific sensors, and in many cases, they only connect to their own proprietary platform brand devices. Atmospheric monitoring systems also usually require technical knowledge for operation or installation, and in many cases, an electrical connection making it challenging to deploy in protected or remote areas [12]. To make this information more accessible some low-cost devices have been developed to analyze the behavior of the environment. Some implementations integrate low-cost sensors and embedded systems to facilitate numerous applications [3,13–16]. Many prototypes are based on Arduino technology, an open source microcontroller [17], to perform this task. For example, Krejcar [18] presents a system to monitor a home weather station fully controlled using a PC, USB, or RS322 connection and C#, all the measures are gathered by an ATmega16 and sent via USB to the main PC intended for indoor use. Alternatively, Brito et al. present a free software-based open source weather station with the possibility of enhancements, using both a low-cost commercial sensor and own built sensors, to help minimize costs [19]. The sensor is shielded from radiation to protect their measurements, and the gathered information is shared to an Arduino UNO through both digital or analog pins and later sent to a Raspberry Pi via I2C bus via wired communication. Some implementations also use WiFi connectivity. Sarkar et al. developed a measuring system with WiFi connection based on Arduino UNO with a 9 V battery for standalone operation[20]. Implementations have also been accomplished with ZigBee connectivity with an Arduino-based system for data transmission to a computer with a maximum distance of 4 km [21]. Similarly, Hussein, et al. used an Arduino with ZigBee module for data transmission and another for reception and storage in an SD [22]. In addition, Carlos-Mancilla et al., built a measurement system oriented to the education of mechatronics, developed using low-cost devices, the Sparkfun weather station card, and data publishing to a server or cloud using ZigBee [23]. Using long-range and low-consumption networks such as LoRa, has also been developed for an Arduino-based energy-efficient climate monitoring system that sends the data to the cloud [24]. Other systems have been designed with radio frequency communication like [25], which proposed a design based on Arduino with protected sensors using their own crafted shields. Finally, there has been some Global System for Mobile Communications (GSM) implementations [26–28]. Most of the aforementioned systems do not have a solar PV charging system or even a battery for the stand-alone operation, which makes their installation challenging in non-connected regions or sites. Additionally, some systems do not integrate a backup system, the cloud transmission requires additional hardware or does not have an internet connection, the sensors are not correctly protected from the environment or requires a ground truth comparison to establish system reliability and accuracy. To overcome these limitations, the low-cost climate monitoring system developed here integrates double verification for humidity, temperature, light radiation, and pressure sensors, which are often biased by the effect of moisture, wind, or solar radiation. The system described here also includes wind speed and rain gauge sensors. In addition, a solar charging and 3G connection system allow the sending of data to the cloud, remote programming of the system, and remote monitoring of the health status of the sensors at any time. These features facilitate the deployment of the system and the use in collaborative sensing tasks [29] for making climate monitoring networks able to be both operated and used by professionals as well as the general public.

2. Hardware description

This work presents the fully free and open source hardware (FOSH) [30,31] integration of a weather station that measures wind speed, rain gauge, atmospheric pressure, relative humidity, temperature, light radiation and carbon dioxide (CO_2). The variables were selected to be able to derive climate measurements and at the same time maintain a low-cost budget. The wind speed is measured with an analog mechanical anemometer and can read up to 32.4 m/s. The rain gauge was measured using an innovative optical sensor with a minimum resolution of 0.02 mm, with serial $RS232/TTL$ communication. This sensor output, however, is ASCII code so it was necessary to develop a library to read it. For humidity, temperature and pressure measurements respectively, two SHT40 and BMP391 sensors were installed and used in different arms of the station to return averaged readings and to detect measurement errors. All these sensors communicate using Inter-Integrated Circuit (I2C), which facilitates their reading, wiring, and the addition of new sensors in the future. Monitoring ambient light radiation is carried by the BH1750 sensor, which has a hemispherical coating and communicates via I2C. The energy of the system is managed by a circuit (Sunflower) that includes an MPPT (Maximum Power Point Tracking) and allows charging a one-cell LiPo battery of 6000mAh using a solar PV module. The manager also provides converters switched to have DC outputs of 3.3 V, 5 V, 9 V, and 12 V. Additionally, to know the energy status of the system, two INA219 current and voltage sensors were installed, one to monitor the main battery and the second for the solar PV to anticipate failures. Finally, a temperature and humidity sensor TH02 was installed inside the main system enclosure to monitor system temperature and humidity, in order to detect a possible water leakage into the box.

The proposed hardware provides several advantages:

- Facilitates the acquisition of climatic and some environmental variables, mainly for smart agriculture applications;
- Communicates wirelessly in real-time, and simply by swapping the MCU (Microcontroller Unit) can change communication from WiFi to 3G, and can be managed from a cloud console independent of the data transmission;
- It is flexible system using free and open source software (FOSS), which allows integration with other FOSH systems to automate actions such as irrigation systems or retractable roofs;
- Some measurements are acquired from different sensors to reduce failures and validate possible data errors;
- The system is powered by solar energy using photovoltaics and is totally autonomous. It also has a second backup battery, and both software and firmware can be changed remotely OTA (Over The Air).

3. Design files

Fig. 1 shows the wiring between the electronic elements of the device including the Sunflower circuit that manages the charge of the main battery through the solar module. The main component is the MCU (Argon-Boron) to which the sensors are connected through the I2C, serial and analog ports.

3.1. Design files summary

This section describes each of the files necessary for the construction of this project. The Table below also indicates its location, all files are available in both STL and STEP formats.

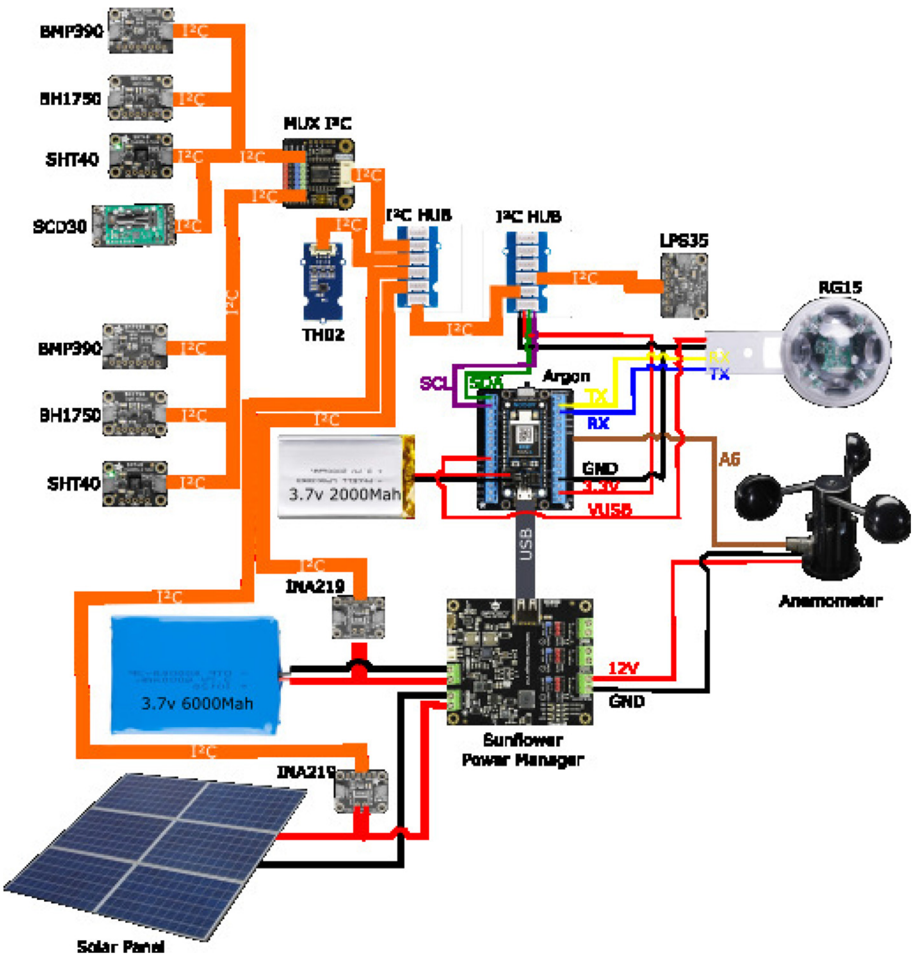


Fig. 1. Schematic of fully autonomous open source climate station for smart agriculture applications.

Design file name	Open source license	Location of the file
AcrylicBase.stl	GNU GPL v3.	https://osf.io/3pfx6/
AcrylicBase.step	GNU GPL v3.	https://osf.io/6qzak/
AnemometerBase.stl	GNU GPL v3.	https://osf.io/g45j6/
AnemometerBase.step	GNU GPL v3.	https://osf.io/hgvx7/
ArmBottom.stl	GNU GPL v3.	https://osf.io/4gdrw/
ArmBottom.step	GNU GPL v3.	https://osf.io/jnbmx/
ArmPlate.stl	GNU GPL v3.	https://osf.io/3hts8/
ArmPlate.step	GNU GPL v3.	https://osf.io/duq2e/
ArmTop.stl	GNU GPL v3.	https://osf.io/bvy4g/
ArmTop.step	GNU GPL v3.	https://osf.io/eh3z5/
LPS35Tube.stl	GNU GPL v3.	https://osf.io/qub7g/
LPS35Tube.step	GNU GPL v3.	https://osf.io/v7h4u/
PlugAntennas.stl	GNU GPL v3.	https://osf.io/v5se7/
PlugAntennas.step	GNU GPL v3.	https://osf.io/qc2fr/
RainGaugeBase.stl	GNU GPL v3.	https://osf.io/wycga/
RainGaugeBase.step	GNU GPL v3.	https://osf.io/s2ue6/
SolarPanelBar.stl	GNU GPL v3.	https://osf.io/bszqa/
SolarPanelBar.step	GNU GPL v3.	https://osf.io/bv2f8/
SolarPanelClamp.stl	GNU GPL v3.	https://osf.io/fjz8w/
SolarPanelClamp.step	GNU GPL v3.	https://osf.io/uh57d/
THPCO2.stl	GNU GPL v3.	https://osf.io/epy9r/
THPCO2.step	GNU GPL v3.	https://osf.io/4emjp/
TubeBaseBottom.stl	GNU GPL v3.	https://osf.io/xk53c/
TubeBaseBottom.step	GNU GPL v3.	https://osf.io/svnmp/
TubeBaseTop.stl	GNU GPL v3.	https://osf.io/4fzc5/
TubeBaseTop.step	GNU GPL v3.	https://osf.io/hvujz/
ArmAssembly.pdf	GNU GPL v3.	https://osf.io/da7bc/
TotalAssembly.pdf	GNU GPL v3.	https://osf.io/u3k78/
MainCode.ino	GNU GPL v3.	https://osf.io/7fbcp/
Schematic.pdf	GNU GPL v3.	https://osf.io/8n49j/

- AcrylicBase, Base to fix the electronic components inside the box.
- AnemometerBase, is the part where the anemometer is assembled and fits into a 1” PVC tube, the anemometer is fixed with M4 bolts and nuts.
- ArmBottom, ArmPlate, ArmTop and THPCO2, are part of the assembly for each arm, and fixes the sensors SHT40, BMP390L, BH1750, SCD30.
- LPS35Tube is for assembling the LPS35HW sensor, it is fixed with M3 screws and fits inside a PVC pipe.
- PlugAntennas, it is a plug to cover perforations that are made to connect external SMA antennas, the use of external antennas is optional.
- RainGaugeBase, it is the base of the RG15 sensor, it is fixed as a clamp to one of the PVC pipes and to the sensor with M4 screws.
- SolarPanelBar and SolarPanelClamp, are the pieces that are used to fix the solar panel, the bar is fixed to the clamp that is attached to the PVC pipe, two equal pieces are required.
- TubeBaseBottom and TubeBaseTop, are two pieces necessary to fix centered the PVC pipe inside the bollard (1) used in the base.
- ArmAssembly and TotalAssembly, are drawings of the assembly of the parts of one of the arms and of the total assembly respectively.
- MainCode is the main source code used to read the sensors, and send the data to the cloud, it has adjustable parameters.
- Schematic is a drawing where the electrical connections are shown in a simplified way, it includes the power connections and that of all the sensors.

4. Bill of materials

This section presents a list of the parts that must be purchased for the manufacture of this device, including the current cost and a possible supplier. The different values at the end of the table represent the two communication alternatives, the

Table 1
Bill of materials.

Designator	Component	Qty	Unit cost	Total cost	Source of material
Boron 2G/3G	MCU	1	$80.65	$80.65	t.ly/hNmI
Argon WiFi	MCU	1	$27.92	$27.92	t.ly/olZ0
Terminal Block	Base MCU	1	$14.95	$14.95	t.ly/GrLp
BMP390L	Pressure Sensor	2	$10.95	$21.90	t.ly/Umk5
LPS35HW	Pressure and Temperature Sensor	1	$12.50	$12.50	t.ly/nd1I
BH1750	Luxometer	2	$4.50	$9.00	t.ly/6vGE
SHT40	Temperature and Humidity Sensor	2	$5.95	$11.90	t.ly/0QGU
INA219	Power Sensor	2	$9.95	$19.90	t.ly/54GI
Anemometer	Sensor	1	$44.95	$44.95	t.ly/oL8Z
Optical Rain Gauge	Sensor	1	$99.00	$99.00	t.ly/rhoi
Multiplexer I2C	Interface	1	$6.90	$6.90	t.ly/O0ai
Grove - I2C Hub	Connector	2	$1.70	$3.40	t.ly/LR3E
G.-I2C Hub	Connector	2	$3.20	$6.40	t.ly/r5m1
G.-Screw Terminal	Cable	1	$4.30	$4.30	t.ly/WpVi
G.-Female Jumper	Base	1	$2.10	$2.10	t.ly/GJHi
G.-Wrapper 1*1	Base	1	$2.10	$2.10	t.ly/0Qxh
G.-Wrapper 1*2	Controller	1	$29.90	$29.90	t.ly/Os5T
Solar Panel	Panel	1	$43.80	$43.80	t.ly/2XZx
Qwiic cable	Cable	5	$1.50	$7.50	t.ly/JA0C
Qwiic OpenLog	SD log	1	$16.95	$16.95	t.ly/wdw0
LiPo 6Ah	Battery	1	$29.95	$29.95	t.ly/LsLW
LiPo 2Ah	Battery	1	$12.95	$12.95	t.ly/mFOt
Cable 4X 22 AWG	Cable	0.25	$30.00	$7.50	t.ly/FXJb
Seahorse SE-300F	Box	1	$33.42	$33.42	t.ly/eRDY
ASA filament	Structural	0.4	$29.99	$12.00	t.ly/9cQJ
Enclosure Gland PG7	Structural	1	$8.99	$8.99	t.ly/HOL8
Pipe PVC 1-in	Structural	1	$3.79	$3.79	t.ly/nj0q
Tee PVC 1-in	Structural	8	$1.41	$11.28	t.ly/Bo7K
Two Conduit Fittings	Structural	1	$2.25	$2.25	t.ly/hyL3
Two Conduit Fittings	Structural	1	$2.25	$2.25	t.ly/hyL3
Conduit Cement	Structural	1	$5.08	$5.08	t.ly/zJHk
Clear silicone 2.8-oz	Sealed	1	$4.28	$4.28	t.ly/En7q
				$564.51	Tot. Boron
				$511.78	Tot. Argon

Boron in case of using 3G communication, or the Argon in case of using WiFi communication. Some elements for mounting the open source weather station such as cement, ties and fastening bolts were not included since these elements depend on the installation method and their spectrum is very broad being dependent on the location for installation. The use of ASA as a printing material can be reviewed at [32] (See Table 1).

5. Build instructions

Fig. 2, shows the assembled mechanical structure. For ease of construction and acquisition of materials, most of the structure is assembled with 1 inch PVC pipes of 200 psi used to transport water, and their respective accessories such as tees, plugs and clamps, which are widely available throughout the world. The PVC pieces were joined using PVC glue to achieve the structure of the Fig. 2. The Figure also shows the 3-D printed parts in the assembly. The 3-D printed parts can be manufactured using any self replicating rapid prototyper (RepRap)-class fused filament fabrication (FFF) system [33,33] or fused particle fabrication/ fused granule fabrication (FPF/FGF) system [34,35].

Table 2 describes each of the elements in the mechanical assembly. Next, a suggested sequence for the construction of the system is described and the previous sections in this work will serve as support:

- Initially, the AcrylicBase is laser cut. And all the parts described in the Table in the section Design File Summary are 3-D printed using ABS (acrylonitrile butadiene styrene) and PLA (polylactic acid) with 25% hexagonal infill, and 0.3 mm layer height. This ensures that all of the components can be digitally replicated with a distributed manufacturing method [36–38] even off grid [39,40]. In addition, all the components are available in both STL and STEP format for different 3-D printing technology or setups as well as for any necessary customization or changes.

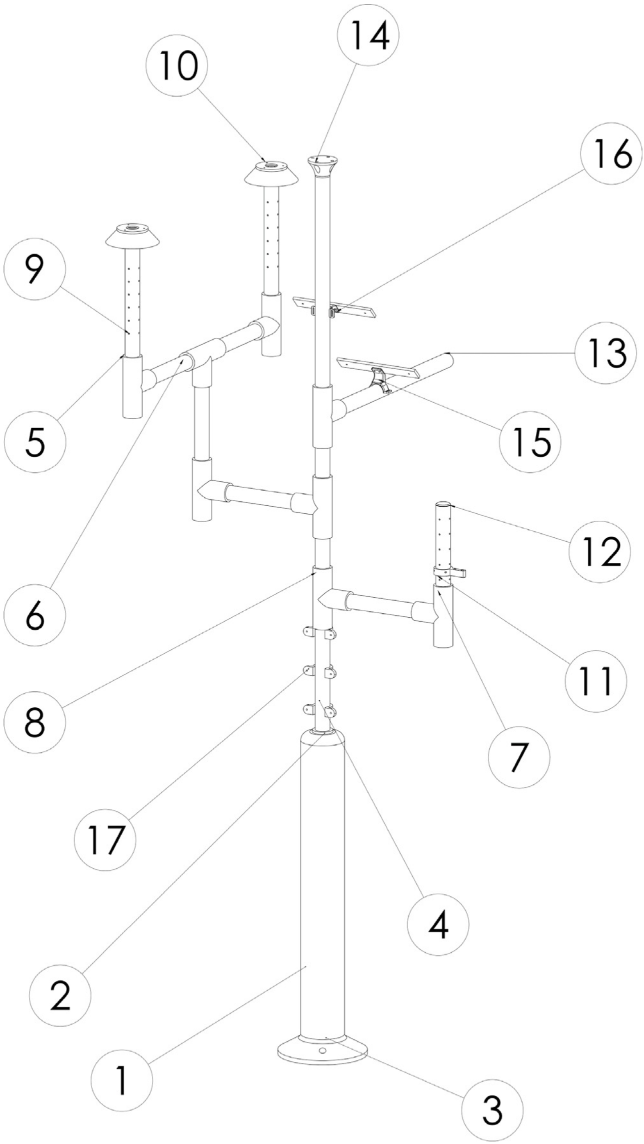


Fig. 2. Total assembly of the climate station.

Table 2
Required of elements for the main assembly.

Part number	Part Name	Quantity
1	Bollard	1
2	TubeBaseTop	1
3	TubeBaseBottom	1
4	1inPVC_pipe1m	1
5	1inPVC_Tee	8
6	1inPVC_pipe20cm	5
7	1inPVC_pipe20cm_holes	1
8	1inPVC_pipe10cm	2
9	1inPVC_pipe30cm_holes	2
10	Illumination_Assembly	2
11	RainGaugeBase	1
12	LPS35Tube	1
13	1inPVC_pipe50cm	2
14	AnemometerBase	1
15	SolarPanelClamp	2
16	SolarPanelBar	2
17	1inPVC_Strap	3

- Insert the tube (4) into the piece (2), and then introduce the tube (4) into the bollard (1) making sure that the piece (2) is centered on top of (1). At the bottom of the bollard, position the piece (3) which will help keep the tube and structure centered. In order to increase the mass and lower the center of gravity to improve stability, the bollard needs to be filled using gray concrete and let dry for at least 24 h.
- The PVC structure must be assembled following the measurements in Table 2, fixing the Tees with conduit cement. In this case, a recommended structure is provided, but adjustments can be made if necessary.
- Extension cables (4 $\times$ 28 AWG) must be soldered, for the sensors in each of the arms, the anemometer, the rain sensor, and the solar PV panel following the Fig. 1.
- Next, for the main box preparation, six holes for PG7 must be distributed on the lower part of the box, and the AcrylicBase piece and the PVC clamps should be employed as a template for perforations inside the box. To ease the work a stepped drill can be used.
- All electronic components must be fixed on the acrylic base, and connected following the schematic described in Fig. 1.
- Fix the MCU, the batteries, the INA219(s), the Sunflower power manager, the TH02, the MUX, and the I2C Hubs to the AcrylicBase, and place it inside the central Box. In the recommended structure, the cable extensions were 2 m, and the excess cord rolls into the central box of the system. See Fig. 3. Use PG7 plug to introduce the cables protecting the system from moisture.
- All the screws and PG7 nuts must be sealed with clear silicone to waterproof the system.
- The pieces ArmBottom, ArmPlate, ArmTop, and THPCO, are assembled for each of the arms (10), the sensors are fixed with the extension cable. And the screw holes and joints between pieces are sealed with clear silicone to reduce leaks.
- The anemometer is fixed to the (14) support with M4 screws and nuts, and later inserted and set on the center (13) PVC tube with a screw.See Fig. 4
- The rain sensor is fixed with the (11) RainGaugeBase piece, also with M4 screws and nuts, on (7) tube the LPS35HW pressure sensor is fixed using the (12) LPS35Tube piece, inserted into the (7) tube and sealed with a 1 inch plug (Fig. 5).
- The PV module is fixed using the (16) SolarPanelBar and (15) SolarPanelClamp pieces, the angle can be adjusted at the same angle of the location latitude plus 15° during winter and minus 15° during summer and facing Equator line to make it perpendicular to the Sun incidence.

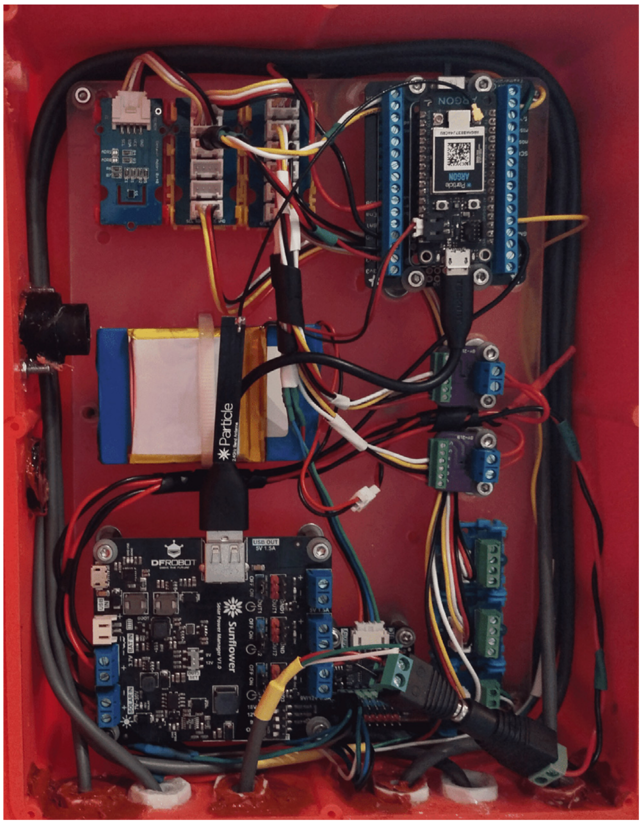


Fig. 3. Central box components and connections.

Fig. 4. Anemometer and arms assembly.

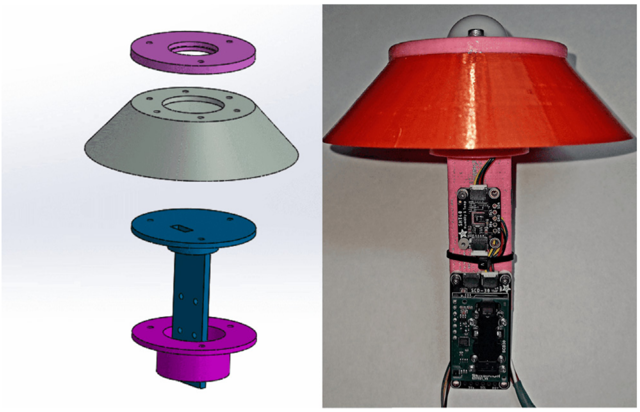


Fig. 5. Illumination sensor assembly.

Fig. 6. Fully assembled Weather monitor system.

- Next, for the main box preparation, six holes for PG7 must be distributed on the lower part of the box, and the AcrylicBase piece and the PVC clamps should be employed as a template for perforations inside the box. To ease the work a stepped drill can be used.
- All electronic components must be fixed on the acrylic base, and connected following the schematic described in Fig. 1.
- All the screws and PG7 nuts must be sealed with clear silicone to waterproof the system.
- Finally, the program is downloaded to the MCU, and if everything is fine, the project is complete. The Fig. 6.

6. Operation instructions

After system assembly, the next stage is data acquisition and processing. The first thing is to register the MCU on the Particle platform [41]. This platform allows different cloud interactions such as flashing and updating code or check MCU health. If the Argon MCU is used, it will be automatically associated with the bound WiFi network used in the configuration. When using the Boron MCU, it is necessary to install the Sim Card and have a balance (dollars) in the cloud to use the network. Additionally, for Boron, it is recommended to download the program locally to avoid consuming the data balance in this assignment. Next, before flashing the code, the parameters in Listing 1: the TOKEN of the Ubidots storage account, and the name of the device should be changed to upload the code into the MCU.

Listing 1: Adjustable parameters

```
#define TOKEN ‘‘XXXXXXXXXXXXXXXXXXXX"
#define DEV1 ‘‘AGR070706"
```

After program uploading, the MCU will return multiple connection data and the output shown in Listing 2. Such information is included in the code to facilitate debugging for users. And it is the resulting sensor state of the scanning and enabling of the sensors connected to the I2C bus and the multiplexer. The OK status of each sensor indicates that it is connected and functional and ER that it is disconnected or had a problem.

Listing 2: Output at startup

```
0000016439 [app] INFO: B1750: Scann OK
0000016439 [app] INFO: B1751: Scann OK
0000016440 [app] INFO: HDC10: Scann OK
0000016440 [app] INFO: I219B: Scann OK
0000016440 [app] INFO: SHT40: Scann OK
0000016441 [app] INFO: SHT41: Scann OK
0000016441 [app] INFO: I219C: Scann OK
0000016441 [app] INFO: LPS35: Scann OK
0000016442 [app] INFO: SCD30: Scann OK
0000016442 [app] INFO: BM390: Scann OK
0000016442 [app] INFO: BM391: Scann OK
0000016812 [app] INFO: SHT40: Begin OK
0000016815 [app] INFO: SHT41: Begin OK
0000016819 [app] INFO: LPS35: Begin OK
0000016849 [app] INFO: SCD30: Begin OK
0000016864 [app] INFO: BM390: Begin OK
0000016879 [app] INFO: BM391: Begin OK
0000016884 [app] INFO: LPS35: Begin OK
```

Finally, in the Listing 3, a typical example of running output is shown, it can be seen that the MCU publishes the value of each variable, all this output is programmed within the code to facilitate debugging, the data is sent to the cloud to its processing and application in real-time, each sensor sends all the available variables and its respective unit of measurement, the output is presented every 60 s in this case, this parameter can be adjusted in the code. In addition to the variables of the sensors, at the end some variables related to the health of the MCU are published, the voltage of the backup battery (ARG01: Voltage) connected directly (not the main one of the system), the available RAM (ARG01: F Memory), if it is charging, that is, powered by USB (ARG01: Charger).

Listing 3: Output data

```
0000180256 [app] INFO: ARG01: Cloud connected
0000181543 [app] INFO: IN219: Voltage0 3.94 mV
0000181543 [app] INFO: IN219: Current0 −53.10 mA
0000181544 [app] INFO: IN219: Shunt0 −5.29 mV
0000181544 [app] INFO: IN219: Voltage1 0.59 mV
0000181545 [app] INFO: IN219: Current1 −0.50 mA
0000181545 [app] INFO: IN219: Shunt1 −0.03 mV
0000181546 [app] INFO: HDC10: Tempera. 24.64 C
0000181546 [app] INFO: HDC10: Humidity 84.66 %
0000181547 [app] INFO: B1750: Light 0.83 lux
0000181547 [app] INFO: B1751: Light 2.50 lux
0000181548 [app] INFO: SHT40: Tempera. 24.96 C
0000181548 [app] INFO: SHT40: Humidity 68.26 %
0000181548 [app] INFO: SHT41: Tempera. 24.50 C
0000181549 [app] INFO: SHT41: Humidity 69.61 %
0000181549 [app] INFO: BM390: Tempera. 25.41 C
0000181550 [app] INFO: BM390: Pressure 884.56 hPa
0000181551 [app] INFO: BM391: Tempera. 24.71 C
0000181551 [app] INFO: BM391: Pressure 854.68 hPa
0000181552 [app] INFO: LPS35: Tempera. 27.64 C
0000181552 [app] INFO: LPS35: Pressure 854.35 hPa
0000181553 [app] INFO: SCD30: CO2 620.00 ppm
0000181553 [app] INFO: SCD30: Tempera. 26.00 C
0000181554 [app] INFO: SCD30: Humidity 63.56 %
0000181554 [app] INFO: RG15R: Acc. 0.00 mm
0000181554 [app] INFO: RG15R: EventAcc 0.00 mm
0000181555 [app] INFO: RG15R: TotalAcc 188.18 mm
0000181555 [app] INFO: RG15R: RInt 0.00 mmph
0000181556 [app] INFO: WINSP: Wind Sp. 10.30 mph
0000181556 [app] INFO: ARG01: Voltage 4.15 V
0000181557 [app] INFO: ARG01: F Memory 113008 bytes
0000181557 [app] INFO: ARG01: Charger 0
0000181558 [app] INFO: ARG01: Power 0
```

Additionally, to remotely perform maintenance tasks or re-establish the system, two functions were included within the code that can be manipulated using the Particle console in the cloud, the "ctrlReset" function and the "ctrlSafem" function, respectively allow reboot the MCU and enter it into safe mode, the input parameter is "yes". Particle is the brand of MCUs that are used in this project, and are very useful because it provides a free platform in the cloud, where the MCU is updated and monitored. This allows us to remotely, as long as the device has internet access, adjust the program, update the firmware and monitor its health status. To send the information from the sensors to the cloud, in this case we use Ubidots, however you can use any platform that can receive information sent by MQTT. Ubidots allows receiving, storing and graphing the data in real time. In case of using the 3G network, the cost depends on the data traffic, linked to the sampling, in our case using a third party sim card, this had consumptions of less than 3 USD per month.

7. Validation and characterization

To validate data acquisition, the recorded information was plotted with the data provided by two weather stations named "Torre Siata" and "AMVA" of the "Sistema de Alerta Temprana del Valle de Aburrá" SIATA. The SIATA is a Science and Technology project developed by the local authority of Medellín, Antioquia. That deploys a web of measurement stations located at different city points for analysis and early prevention of disasters. The SIATA weather stations located at a distance of 1.6 km (Torre Siata) and 1 km (AMVA) from the installed system serve to establish the reliability of the designed station. Additionally, a Vantage Pro meteorological station presented in the plots as REF, was used as a reference to determine the scale of temperature humidity, pressure, and radiation data.The minimum, maximum and mean absolute error were calculated using SIATA stations as a reference, and are presented for each measurements in Tables 3–6.

Table 3
Humidity error.

Day	7			8			9			10		
Error [%]	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
SCD30	0.0435	7.4114	4.4585	0.0530	7.4965	4.6385	2.0749	8.6835	5.6339	0.0040	11.8182	6.7630
SHT40	0.0006	2.9242	1.0166	0.0014	4.4452	1.0141	0.0115	2.5441	1.0044	0.0015	6.3542	1.0593
SHT41	0.0001	3.4034	0.5049	0.0001	3.9767	0.5801	0.0003	2.1468	0.4916	0.0020	6.1364	1.0593

Table 4
Temperature error.

Day	7			8			9			10		
Error [C°]	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
BM390	0.0001	1.1759	0.3233	0.0006	1.2022	0.3070	0.0003	0.6811	0.2695	0.0002	0.9876	0.2416
BM391	0.0002	0.9159	0.2581	0.0000	0.8589	0.2442	0.0001	0.5141	0.2410	0.0000	0.8281	0.2367
LPS35	0.0005	1.5452	0.3483	0.0022	1.4037	0.3088	0.0001	0.6321	0.2085	0.0001	1.6110	0.2661
SCD30	0.0000	1.5185	0.5455	0.0009	1.6152	0.5035	0.0136	0.7623	0.3946	0.0034	1.5410	0.3829
SHT40	0.0001	0.7056	0.2072	0.0009	0.5890	0.2149	0.0001	0.3659	0.2078	0.0005	0.6437	0.2452
SHT41	0.0000	0.9787	0.2732	0.0003	1.0088	0.2514	0.0001	0.6260	0.2400	0.0000	0.7942	0.2279

Table 5
Pressure error.

Day	7			8			9			10		
Error [hPa]	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
BM390	0.0012	0.6271	0.3115	0.0002	0.7577	0.3397	0.0003	0.6811	0.2695	0.0004	0.6743	0.3272
BM391	0.0000	0.0780	0.0168	0.0000	0.0836	0.0192	0.0001	0.5141	0.2410	0.0000	0.1245	0.0195
LPS35	0.0000	0.4452	0.1563	0.0001	0.5269	0.1730	0.0001	0.6321	0.2085	0.0002	0.5238	0.2376

Table 6
Solar radiation error.

Day	7			8			9			10		
Error [W/m^2]	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
B1750	0.00	60.06	8.01	0.00	47.49	9.77	0.00	51.23	7.87	0.00	45.02	7.54
B1751	0.00	56.15	7.37	0.00	58.93	9.68	0.00	65.18	3.42	0.00	47.38	2.19

7.1. Humidity

For humidity measurement, the system uses three sensors, an SCD30 and two SHT40 (named SHT40 and SHT41). In the case of the SCD30, there is an average error higher than the rest of the humidity and temperature sensors, see Figs. 7, 8, this is because humidity and temperature measurement in this device serves as a correction to the CO2 detected values and are not as accurate as a dedicated one.

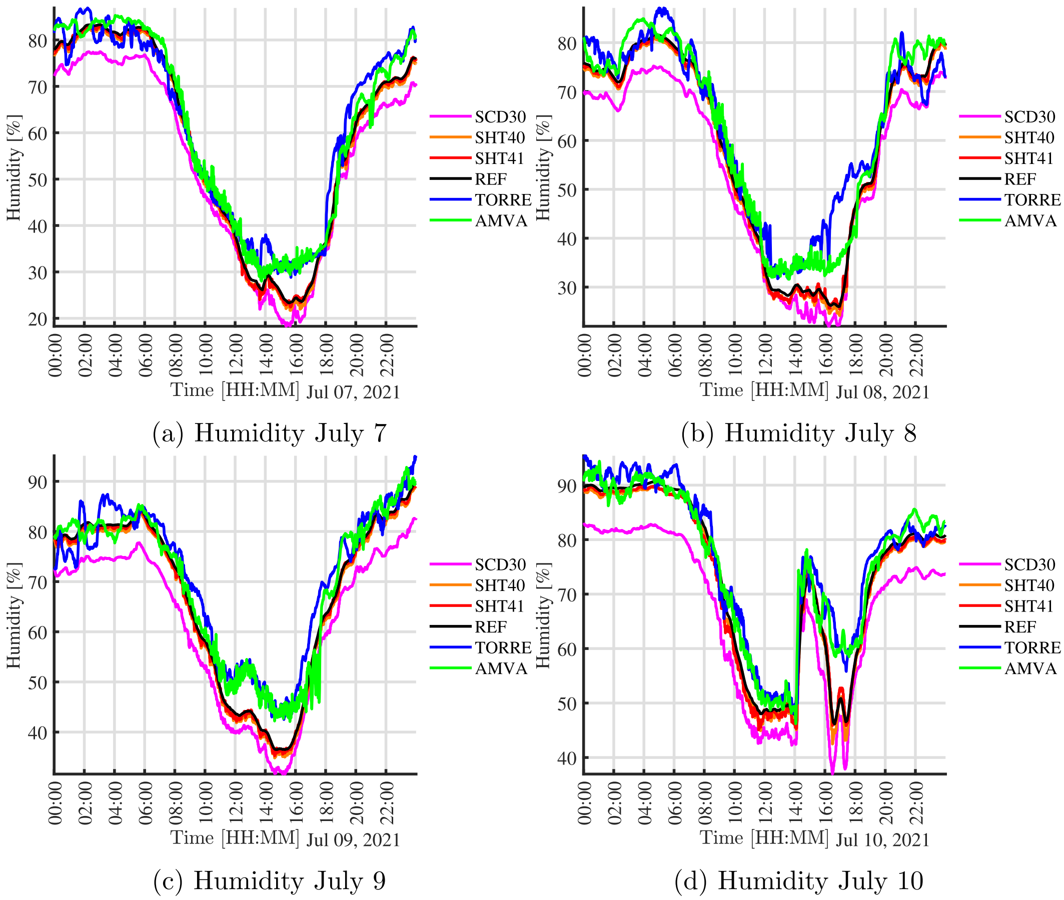
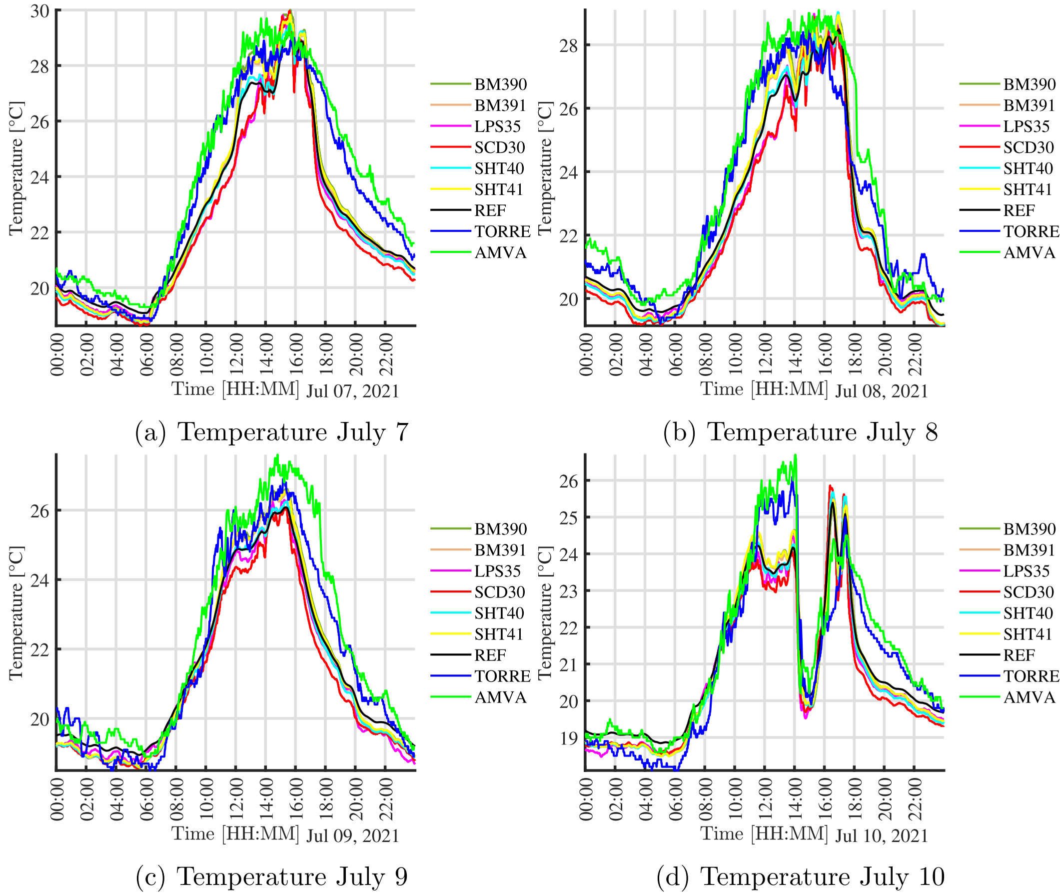


Fig. 7. Humidity (percent) as a function of time.



(a) Temperature July 7
(b) Temperature July 8
(c) Temperature July 9
(d) Temperature July 10

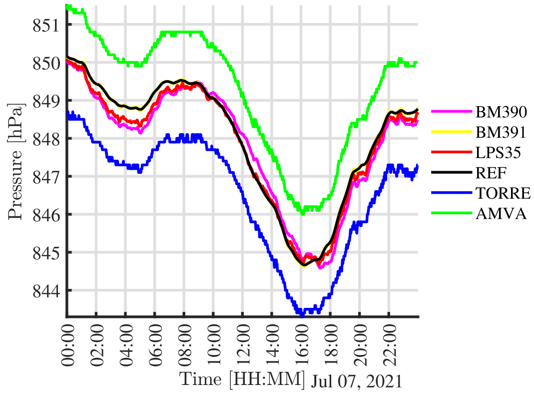
Fig. 8. Temperature measurements as a function of time.

7.2. Temperature

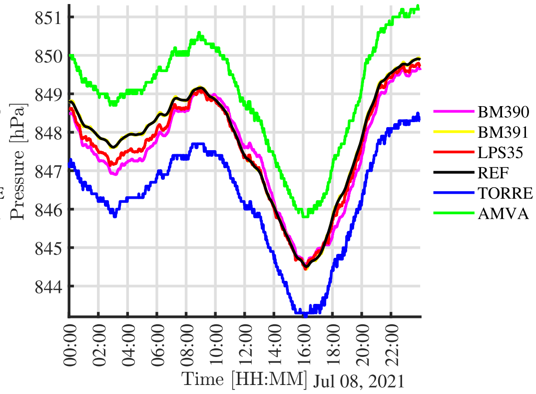
For temperature five sensors were used two SHT40, two BMP390, and an SCD30, all with mean errors under one degree. The measurements profile of the sensors is very similar to the references and responsive to climate changes, as seen on July 10. That day precipitation occurs in the afternoon hours, which shows a reduction in the temperature measure. Fig. 8 does not follow the behavior of other days without rain, similarly to humidity, see Fig. 7, which present a peak in the same period that suggests a proper functioning of the system.

7.3. Pressure

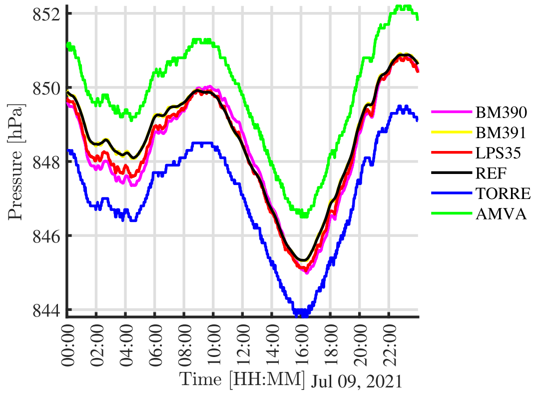
The pressure is shown in Fig. 9 and the error is shown in Table 5. As can be seen, the pressure plot shows the same profile with three different scales, this behavior is mainly caused for the location of the measurement system, which differs in height, nevertheless, overall behavior shows correlation due to geographical position keeping high similitude with the REF.



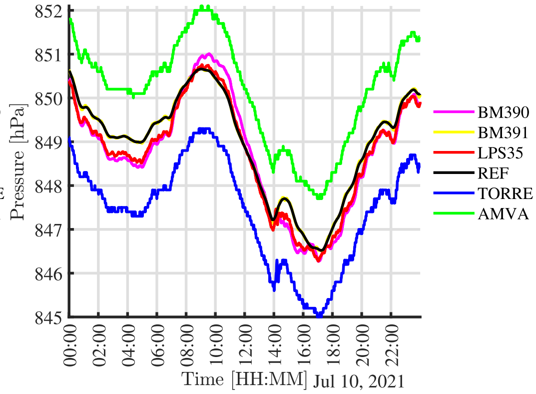
(a) Pressure July 7



(b) Pressure July 8



(c) Pressure July 9



(d) Pressure July 10

Fig. 9. Pressure as a function of time.

7.4. Solar Radiation

Solar radiation was measured using two B1750 (named B1750 and B1751). Nevertheless, this variable was only available at the AMVA station so the Torre Siata is not present in Fig. 10. Additionally, due to system location, the radiation measurements show a variation in scale during the first half of the day when there is no direct light on the sensor, see Fig. 10. However, in the second half of the day, the measurements are comparable to those obtained from SIATA stations which demonstrate system reliability. Although the minimum, maximum, and average error measures are presented for each of the variables (Tables 3–6) and are relatively low, since the stations are not located in the same geographical position, some factors such as reflection shadows, can modify the measurements. This is why the error may not be an appropriate measure for comparing the system. The measurements profiles, however, are highly similar to references that suggest a proper function of the system.

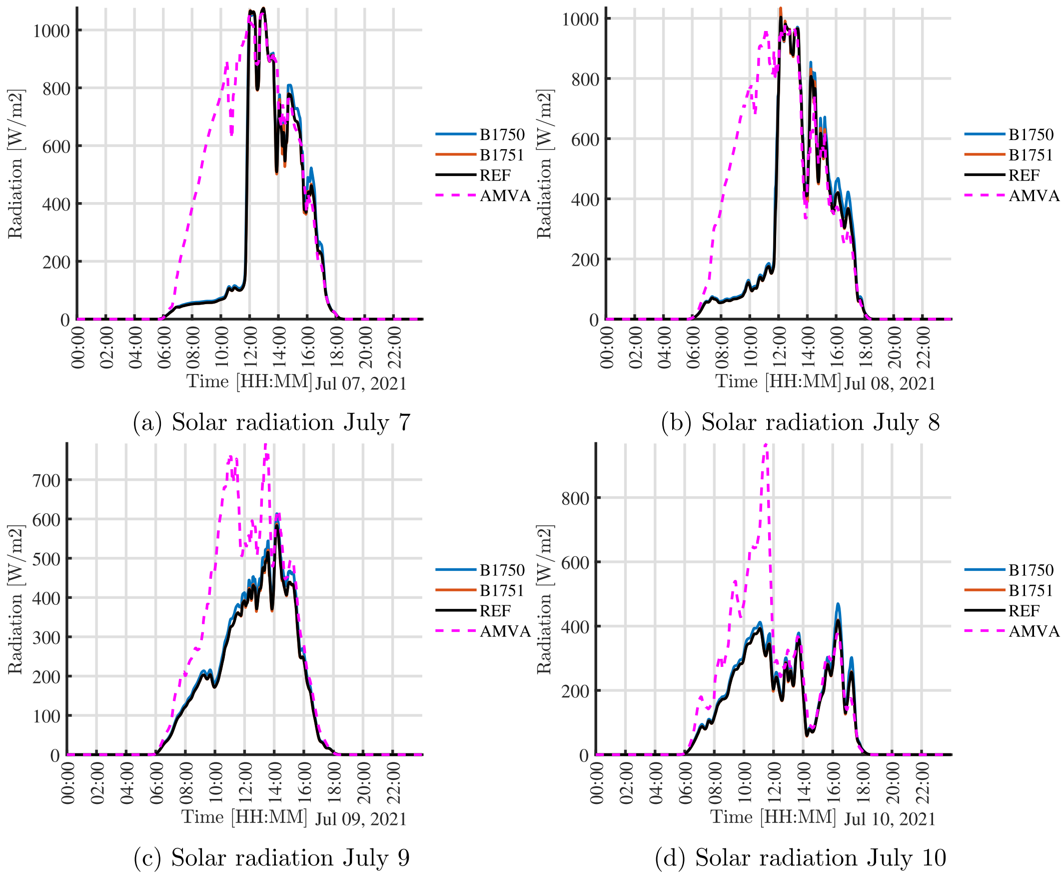
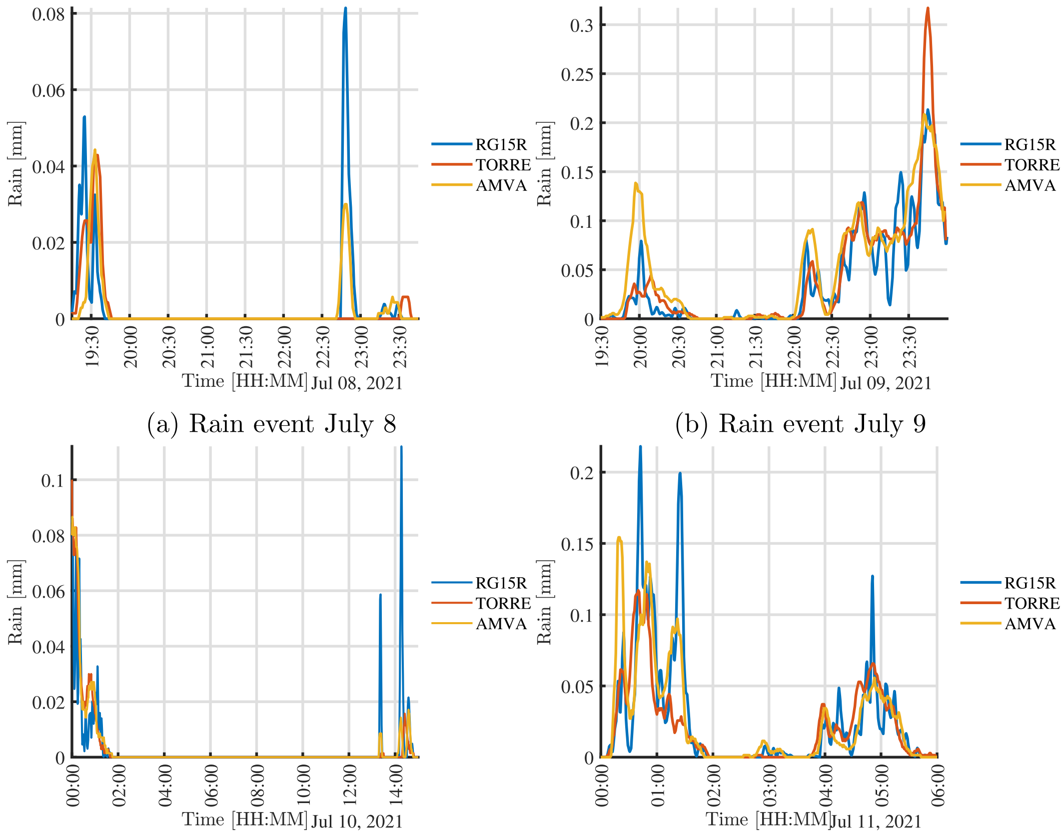


Fig. 10. Solar radiation as a function of time.

7.5. Rain

Finally the rain was measured with RG15R and compared with the references. As this variable is one of the most geographical dependent the absolute error was not calculated. Nevertheless, the general plot behavior shows similitude with the references and detects rain events with different intensity levels. see Fig. 11.



(a) Rain event July 8

(b) Rain event July 9

(c) Rain event July 10

(d) Rain event July 11

Fig. 11. Rain event.

7.6. Wind speed

The wind speed typically has a behavior commonly adjusted to a Weibull PDF, for this reason, Fig. 12 presents the histogram of the acquired data in blue and an approximation of the Power Distribution Function (PDF) in red, for the wind speed on each of the indicated days, showing the consistency of the data. Since Fig. 12 represents a histogram, the y-axis, the frequency, represents the occurrence, i.e. the number of times a measurement occurred, and the x-axis represents the respective velocity in m/s.

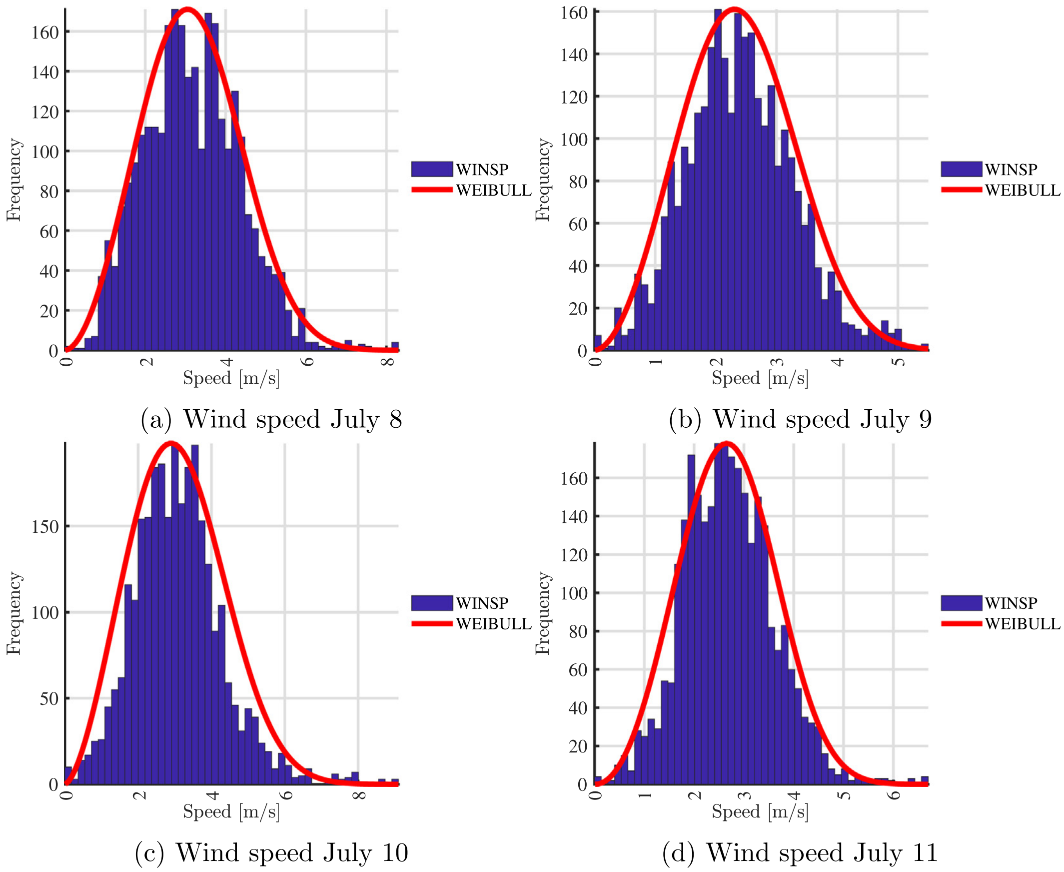


Fig. 12. Wind speed vs Weibull PDF. (WINSP refers to wind speed).

8. Power consumption

As mentioned above, the system has two INA219 sensors that measure current and voltage, one is connected to the battery and the other to the solar panel. The purpose of these sensors is to know in real time the energy absorbed from the battery and the energy generated by the panel, it is also important to remember that the system has a second battery connected to the main MCU as a backup. To evaluate the energy consumption of the system, the battery current was measured when sending data, which is where there is a peak, and in normal operation mode (nominal), this is a common way to estimate the

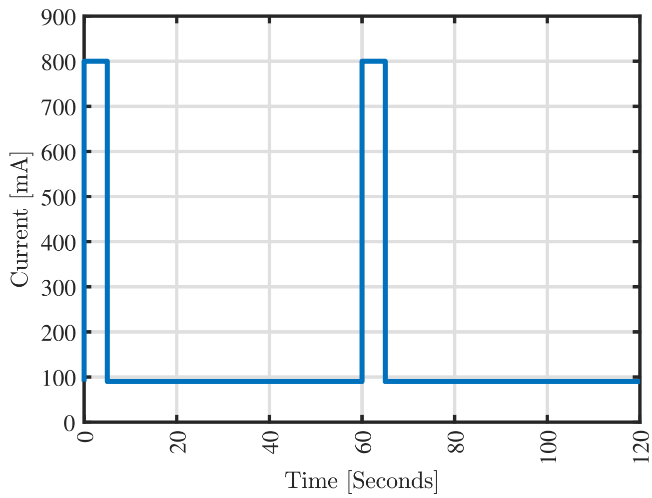


Fig. 13. Power life cycle.

Table 7
Operating time.

MCU	BORON	ARGON
Peak current [mA]	800	200
Nominal current [mA]	100	50
Time [1 min]	1800	17220
Time [2 min]	2220	34320
Time [3 min]	2400	51360
Time [4 min]	2460	68280

life of the battery, an average sending time was also considered. The Fig. 13 shows as an example the approximate cycle when using the Boron MCU, in this case the peak is approximately 800 mA and in nominal mode the consumption is 100. Finally in Table 7, a summary of the system operation time in minutes is presented for sampling times of 1, 2, 3 and 4 min, without considering the PV system load, in the worst case, the battery can operate for 30 h (1800 min), and an estimated energy of 22.2 Wh. The photovoltaic system has a 10 W panel, with an estimated 5 h of radiation effectiveness, it could operate at 50 % and the system would remain charged, this means that the system is oversized, and that these variables are also monitored so that failures can be detected remotely.

9. Discussion and future work

As can be seen by the results in Section 7 the open source low-cost climate station successfully monitors humidity, temperature, pressure, solar radiation, and precipitation (rain). The redundant sensors help to ensure reliable measurements and provide a method for ensuring that the devices are working or need maintenance. The system is self-powering given the PV and has two options for wireless data transfer and logging for IoT purposes. The choice of WiFi or 3G communication system, instead of LoRaWAN or LTE-NB, is that in most developing countries, these are not yet deployed and the installation of a gateway would significantly increase the cost of the system.

In addition to providing power the photovoltaic module can act as a reference cell for solar energy generation capability and agrivoltaic potential in the installation area. Agrivoltaics [42], which is the co-location of crops and PV systems, is growing rapidly and has been shown to improve water efficiency [43] and increase productivity of land [8,44,45] for a wide array of plant-based crops including lettuce [46,47], spinach and strawberries [45], wheat [9], rice [48], grapes [49], potato, celeriac, clover grass and winter wheat [50]. Agrivoltaics has also been found to be beneficial both economically and environmentally in several forms of pasture-based animal husbandry as well such as sheep [51,52], rabbits [53,54] and honey bees [55]. Due in a large part to climate destabilzation from anthropogenic climate change globally farms face increasing pressure from extreme weather events and shrinking margins [56,57]. Agrivoltaics can reduce weather-related financial risk for a landowner. Cuppari et al. found that agrivoltaics increased net revenues relative to a farm-only scenario by 300 to 5,000 percent annually [58]. This is particularly important for crops like strawberries that are subject to great risk via weather and market conditions, as co-location with PV provides diversification to income streams, and reduces revenue volatility and lifting worst case net revenues by 48–53 percent [58]. This study provides a low-cost method of obtaining data that can be used by the agricultural sector to enable professionals in the area to improve harvest yield and production conditions while mitigating risks due to climate change.

Although the system is less expensive than comparable commercial systems it can be reduced further by using recycled filament or shredded feed stock following distributed recycling and additive manufacturing methods for the 3-D printed parts [59,60]. The majority of the costs, however, are in the sensors themselves, which indicates the greatest potential for cost reductions it to apply the open hardware model[61] to making the sensors themselves [62,63]. For example, the electronic boards can be fabricated using open source PCB mills [64–66]. It addition, it is expected that the costs will continue to decline with time because of the trends in the reduction in costs of batteries [67,68] and solar PV modules (decline over 2010–2019 was 82 percent)[69,70]. The system is designed to be modular so that adding other sensors to the assembly is meant to be easy. The code for the existing sensors can be used as templates for expansion. Future work, for example, could add visual imaging, IR imaging, albedo sensing, ground moisture sensing, dust accumulation and spectral analysis.

The main features and limitations of the proposed device are:

- Its assembly is easy and does not require expensive tools for installation. In addition, it is wireless which means that it does not require a electrical or mains connection point.
- The size and shape of the system can be modified which provides greater flexibility and adaptability to different situations or terrain.
- Thanks to the solar charging system and the mounting of the PV module, it is possible to generate energy to power the system and even verify the solar generation levels at different angles or positions.
- Since an open-source MCU and I2C bus are used, it is possible to add or remove the necessary sensors for different studies.
- The measures are similar to those obtained with systems with a higher cost, which facilitates their development for research and development of new technologies while expanding accessibility.

Human and animal rights

No human or animal studies were conducted in this work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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