A low-cost system for real-time measuring of the sunlight incident angle using IoT

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ABSTRACT

The incidence angle of solar irradiance is an important parameter for sizing and locate photovoltaic systems, which affects the installation design and has a high influence in the power production of photovoltaic panels. This angle is traditionally estimated considering the geographical position, however, this approach ignores the existence of local elements that affect the generation, such as weather conditions, topography, constructions with high reflection, among others. Therefore, this work presents the design and construction of a measurement device with nine irradiance sensors, which are located at different angles on two orthogonal axes within a semisphere. Since the angles of the sensors are known, a model to determine the direction of the maximum incidence irradiance, at each instant of time, can be calculated from the on-site measurements. In this way, it is also possible to calculate the panel inclination and orientation producing the maximum power for a particular location. The device acquires the irradiance magnitude in the nine sensors in real time, and it is transmitted using the Internet to simplify data recollection. Finally, the device uses a low-cost platform, which makes possible the adoption of this solution in a wide range of applications, e.g. design, diagnostic or reconfiguration of PV arrays.

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Specifications table:

| Hardware name | Low-cost system for real-time measuring of the sunlight incident angle |
|---|---|
| Subject area | Engineering |
| | Instrumentation |
| | Sunlight incident angle |
| | 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 | $166.94 USD |
| Source file repository | https://doi.org/10.17605/OSF.IO/PFXS7 |

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1. Hardware in context

Photovoltaic (PV) systems are a promising alternative to reduce the use of fossil fuels. One of the main advantages of PV systems concerns the solar irradiance availability [1], which avoids the costs of fuel transportation. The power production of a PV panel depends on the solar irradiance reaching the panel surface, which also depends on multiple factors: incident irradiance, panel orientation and inclination, shading pattern covering the panel, among others [2]. In particular, the solar irradiance available in a geographical location can be estimated from databases [3] or using in-site sensors [4]. Similarly, the panel orientation is defined using a standard expression depending on the place latitude as it is reported in [2,3].

The incidence angle of the solar irradiance has a significant effect on the power production of the PV panel. Such an effect is discussed in [5], where mathematical models are used to design mechanical systems for sun tracking. Those tracking devices have the main objective of optimize, in real-time, the incidence angle of the solar irradiance; unfortunately, that work does not provide experimental verifications of the system applicability and an evaluation of the system precision. A similar work was reported in [4], where the effect of both inclination and orientation angles in the PV power production is studied. The work is based on the mathematical models of multiple cell types, but similar to the previous work, it is based on simulations without providing any experimental verification. The study reported in [6] analyses the impact of the incidence angle on the power production of grid-connected PV system installed on Northern Ireland, which is also based only on simulations. The incident angle also affect other operational aspects of the PV system; for example, in [7] is studied the effect of the incident angle on the power degradation produced by dust accumulation on the panel surface. Such a study proposes an empirical equation, based on experimental data, to estimate the incident angle effect. The previous works demonstrate the usefulness of experimental measurements of the irradiance incidence angle taken at the location of a possible PV installation.

The incident angle of the solar irradiance changes with the place elevation, and it could be affected by large geographical bodies (such as mountains) and constructions reflecting additional solar irradiance to the panel (such as windows), hence the effective irradiance magnitude reaching the PV panels will be different than the value reported by meteorological services. To face those conditions, Kyosemi Corporation (Japan) designed a PV cell with spheric geometry named SPHELAR [8], which has the objective of increasing the power density of PV system. This new geometry was designed to absorb the highest irradiance possible along the day, this based on multiple surfaces with different orientations adjusted to the incidence angles of the solar irradiance along the day. This spherical PV cell was evaluated in [8], where the performances of both spherical and traditional PV cells were contrasted, focusing the study on the power production for different incidence angles of the solar irradiance. The study demonstrated that fine-tuning the inclination and position of both spherical and traditional PV cells have a significant impact on the power production; therefore, such a study puts into evidence the need of devices for measuring, precisely, the incidence angle of the solar irradiance.

Partial shading is another phenomenon affecting the power production of PV arrays formed by series-connected modules, which corresponds to the industrial standard [1]. In particular, if a PV panel is partially shaded, the panel current is reduced in comparison with the string current, which produces the activation of the bypass diode protecting the module. Such a diode activation imposes a negative voltage at the panel terminals, which forces that panel to consume power: this operation condition, known as second-quadrant operation, reduces the power production of the PV system and decreases the panel life-time [9]. The partial shading is caused by objects adjacent to the PV panels such as buildings, posts or even other PV panels; and the shape and severity of the shades change along the day. Therefore, estimating the power production and life-time of a PV system, which is exposed to partial sharing, requires the data describing the shading pattern affecting the PV array. Multiple solutions have been proposed to face this problem: for example, in [10] was analyzed the shape and trajectory of a shading pattern covering a PV system, with the aim of estimating the PV power; however, such a work does not provide experimental verification to demonstrate the applicability and precision of the proposed solution. In any case, the analysis presented in [10] puts into evidence the importance of the shading pattern analysis for commercial PV installations, which could be solved with suitable measurement devices. However, the physical location of those measurement devices must be carefully selected to cover the path of the shades along the day; for example, the measurement devices could be located at the corners of the area in which the PV field will be installed.

The previous literature review shows the need of designing devices for measuring the effect of the incidence angle on the solar irradiance reaching the PV modules, which will be useful to define the geographical location in which a PV system must be installed. Moreover, the device must to take into account the change of the incidence angle along the day: for example, the device reported in [11] is based on five irradiance sensors located on perpendicular planes on a vehicle, which provides information concerning the distribution of the solar irradiance over the vehicle surfaces. Such a device is intended for supporting the design of PV arrays and PV concentrators depending on the vehicle geometry; however, it is not evident the device applicability to classical PV systems. Another solution, presented in [12], concerns a device based on a CMOS sensor to measure the effect of the irradiance incidence angle on the power production. This device uses an electrical motor to rotate the sensor depending on the sun translation, but the electrical power required by the device, and the maintenance required by the mechanical parts, make difficult the autonomous operation of the device. Therefore, it is needed to design devices to measure and store the physical variables required to perform real-time analyses [13] with low-power consumption, which enable the on-field operation for long periods of time. Such conditions were addressed in [14] by proposing a procedure for reducing the
Along the day, both design and optimize PV installations. In particular, the acquired data is used to estimate the angle with the highest incidence (DNI) and shading pattern using an array of thermopiles; however, such a device does not track the sun, hence the angle of the PV installation. Another commercial device is reported in [25], which allows to measure the Direct Normal Irradiance (DNI) and shading pattern using an array of thermopiles; however, such a device does not track the sun, hence the effective irradiance reaching the particular area.

Concerning commercial solutions, the device reported in [24] provides a traditional pyranometer with a manual tilt adjustment; however, such a device measures diffuse irradiance, hence the measure effectiveness depends on a correct prediction of the tilt angle. Moreover, since no additional sensors are available, it is impossible to detect the optimal incidence angle of the PV installation. Another commercial device is reported in [25], which allows to measure the Direct Normal Irradiance (DNI) and shading pattern using an array of thermopiles; however, such a device does not track the sun, hence the DNI value is not correlated with the irradiance incidence angle, hence it is not possible to estimate the optimal inclination of the array.

The previous problems are addressed in this paper by designing an embedded system able to analyze the effect of the irradiance incidence angle on a PV system, which is used to define the optimal panel angle for a particular place including all the practical conditions of the site (partial shading, reflected irradiance, etc.), thus providing high accuracy. The proposed device is formed by nine irradiance sensors located in a semi-sphere, hence each sensor measures the irradiance in a particular plane. In addition, a model is developed from the acquired data to calculate the incidence angle providing the highest PV power production. The device uses wireless internet to transfer the sensors data, where the sampling frequency is adjusted depending on the data variability to reduce the stored data, but enabling the characterization of fast changes on the ambient and shading conditions. The device is powered with a PV panel, an energy management system and a battery, which enable autonomous operation for long periods of time; therefore, a large amount of information can be obtained, which is useful for both design and optimize PV installations. In particular, the acquired data is used to estimate the angle with the highest incidence irradiance for each interval of time, and the best panel angle is obtained from the sum of all the irradiance vectors along the day.

2. Hardware description

The Particle Photon has a WiFi module that allows an Internet connection, and it provides the use of the Particle Build IDE, which is a browser-based portal where the Photon code can be created, edited and saved. In addition, the Particle Photon offers a centralized IoT command center, which provides interfaces to simplify the interaction and management of Particle devices. Therefore, using that tool is possible to monitor the health of the device, regardless of the cloud service adopted. Finally, the sensors are connected to the MCU to enable the data capture, and the PV panel provides autonomy to the device.

The irradiance is measured using TLS2591 sensors, which are high sensibility photodetectors that transforms irradiance intensity into digital signals. Those sensors have high-bandwidth and infrared photodiodes for improved measurement; the sensors also integrate two Analog-to-Digital Converters (ADC) to transform the output current from the photodiodes into a digital signal representing the irradiance in each channel. Moreover, the integration time and signal gain can be configured using digital values to adjust the sensibility. The TLS2591 has an I²C communication interface, which makes simple to exchange information with a microcontroller, and the TLS2591 does not require external conditioning circuitry. Finally, the sensor range is 400 nm–1100 nm [26].
The mechanical structure designed for imposing the sensors orientation, i.e. the sensors arcs, and the supports for the electronic components and PV panel, were all produced using an ABS 3D printer. The base and protective semisphere were constructed using transparent acrylic. As evidenced in other publications [27], the acrylic transmittance is almost uniform in the visible spectrum, thereby it does not affect the wavelength. On the other hand, the acrylic thickness affects the power because the transmittance value is lower than 100%, however, this influences all sensors uniformly. The arcs where the sensors are located were designed with the same shape as the acrylic dome, in order to avoid any influence on the angle of incidence. In other words, the arcs are parallel to the dome surface.

One important aspect was to isolate the electronics support from the device base, which avoids heat transference to the electronic components. The final prototype, depicted in Fig. 1, has the following components: 2.5 W PV panel, DFRobot solar controller, Particle Photon embedded system, Qwiic Shield for Photon, DFRobot Gravity multiplexers, and nine TLS2591 sensors.

Each sensor was enclosed into a custom design capsule with a 1 mm hole, which ensures that the light reaching the sensor is perpendicularly oriented with respect to the sensor plane. Specifically, the hole closes the field of view at an angle of $10^\circ$ approx, as the light travels through the 4.5 mm thickness of the sensor capsule. Such a design isolates the measurement of one sensor from the measurement of the other ones; Fig. 2 shows the designed sensor capsule. The precision and homogeneity of the enclosed sensors were tested using an Ocean Optic HL2000 light source, and the sensors gains were calibrated with a Thorlab PM power measurement device. Therefore, for the same light source, the nine sensors produce the same measurement.

The nine sensors were placed in two semicircular structures (arcs) to measure the light intensity in planes located at $90^\circ$ and $45^\circ$ for each cardinal direction (north, south, west and east), and a single sensor was located at $0^\circ$. Figs. 3 and 4 show the sensors positions, using both top and frontal views, where the $0^\circ$ plane is at the center and top of the device. Sensors 1, 2, 3 and 4 have a $90^\circ$ inclination, while sensors 5, 6, 7 and 8 have a $45^\circ$ inclination.

Such a custom design enables to measure the irradiance at those precise inclination angles, hence the device provides the irradiance components at those particular planes. This is not possible by using multiple classical photodetectors (or pyranometers) pointing at different orientations, since those sensors are not designed to be isolated from each other, hence it is not possible to obtain information of the irradiance component in each particular plane. Therefore, such a classical solution does not allow a precise calculation of the optimal incident angle, since the same diffuse irradiance could reach two or more pyranometers at the same time, thus introducing an error on the angle estimation.

Under the sensors, the device has a 2.5 W PV panel and a 6000 mA battery, which provide complete autonomy; such a PV panel is observed in Fig. 1. The device also includes a Solar Power Manager from DFRobot, which ensures the Maximum power Point tracking (MPPT) in the PV panel and the correct battery management [28]. Under the PV panel is located the IoT hardware, which corresponds to a Particle Photon embedded system formed by a Cortex M3 microcontroller and a WiFi Broadcom module. Such an IoT device collects the sensors data, which is transmitted using a TCP/IP internet protocol. In addition, since each TLS2591 sensor has the same $I^2C$ address, two DFRobot Gravity multiplexers were used to communicate with the nine sensors. Finally, the embedded system has a low-power consumption mode (DeepSleep), which is used to significantly reduce the system energy consumption during the night.

The proposed hardware provides several advantages:

- The IoT characteristics enable the real-time data acquisition, which can be used for improving sun tracking systems; moreover, the device operation can be adjusted depending on the data variability (resolution and sampling time) to reduce power consumption.
The irradiance measured by each of the nine sensors is normal to the sensor plane, hence it is a directional measurement. Such a characteristic enables to calculate the optimal incidence angle with high precision.

- The device is designed with low-cost elements, hence the overall cost of the proposed solution is lower than the cost of a commercial pyranometer and improves the type of measurement because additionally it is possible to have angle information.

3. Design files

Fig. 5 shows the scheme of the proposed device, where the elements and connections are described. The device uses a PV panel as main energy source, a battery for support the device operation under low-irradiance conditions, an energy management system for ensuring the correct battery charge and discharge. The embedded device (Photon WiFi Development Board) is used for signal processing and transmission, and multiplexers are used for I2C communication. Finally, the device has nine irradiance sensors.
### 3.1. Design files summary

| Design file name       | File type | Open source license                      | Location file    |
|------------------------|-----------|------------------------------------------|------------------|
| Box                    | .png      | GNU General Public License (GPL) 3.0     | https://osf.io/wde9j/ |
| ArchSupport01          | .stl      | GNU General Public License (GPL) 3.0     | https://osf.io/zu2wb/ |
| ArchSupport02          | .stl      | GNU General Public License (GPL) 3.0     | https://osf.io/42csd/ |
| BasePlate              | .stl      | GNU General Public License (GPL) 3.0     | https://osf.io/4r8b5/ |
| PanelSupport01         | .stl      | GNU General Public License (GPL) 3.0     | https://osf.io/d54y9/ |
| PanelSupport02         | .stl      | GNU General Public License (GPL) 3.0     | https://osf.io/gnexy/ |
| SensorSupportTop       | .stl      | GNU General Public License (GPL) 3.0     | https://osf.io/dsycg/ |
The ArchSupport01 and ArchSupport02 correspond to the arches where the sensors are positioned.

The BasePlate is the support for the electronic devices.

The PanelSupport01 and PanelSupport02 are the elements that allow the panel to be positioned above the electronic elements attached to the BasePlate. In other words, they are the supports to hold the solar panel.

The SensorSupportTop, SensorSupportBottom and SensorFixer are the pieces that allow to encapsulate the sensors so they can be attached to the arches.

The Schematic presents the electronic schematic of the device, the main components and their connections.

In the main there is a C code to read the sensors and send the information to the cloud. The code can be changed for customization.

### 4. Bill of materials

| Designator     | Component                                | Qty | Unit cost | Total cost | Source of Materials   |
|----------------|------------------------------------------|-----|-----------|------------|-----------------------|
| TLS2591        | Irradiance sensor                        | 9   | $5.95 USD | $53.55 USD | https://www.adafruit.com/ |
| Photon shield  | Qwiic Shield for Photon                  | 1   | $5.95 USD | $5.95 USD  | www.sparkfun.com       |
| Mux            | Gravity I2C Multiplexer                  | 2   | $6.9 USD  | $13.8 USD  | https://www.dfrobot.com |
| Power Manager  | Solar Power Manager 5 V                  | 1   | $7.9 USD  | $7.9 USD   | https://www.dfrobot.com |
| Acrylic Base   | Acrylic Base – 18 cm diameter            | 1   | $5.0 USD  | $5.0 USD   | www.amazon.com         |
| Acrylic sphere | Acrylic sphere                           | 1   | $39.99 USD| $39.99 USD | www.amazon.com         |
| PV Panel       | Solar Panel                              | 1   | $10 USD   | $10 USD    | www.amazon.com         |
| Photon         | Photon WiFi Development Board – Particle | 1   | $19 USD   | $19 USD    | www.sparkfun.com       |
| PLA            | Polylactic acid                          | 1/10| 18 USD    | $1.8 USD   | www.amazon.com         |
| Battery        | Lithium Ion Battery                      | 1   | $9.95 USD | $9.95 USD  | www.sparkfun.com       |

### 5. Build instructions

First, the device base must be cut (Acrylic Base). The base corresponds to an acrylic circle of 18 cm in diameter. Then, the following pieces should be 3D printed, ArchSupport01, ArchSupport02, BasePlate, PanelSupport01, PanelSupport02, SensorSupportBottom, SensorSupportTop and SensorFixer. For that purpose, one can choose to use Polylactic acid (PLA) or Acrylonitrile butadiene styrene (ABS). In this case, the pieces were printed using PLA.

Above the acrylic base, a second base (File: BasePlate) is positioned, which aims to serve as a support for electronic devices, with the exception of the sensors and the solar panel. This base has holes that allow you to fix each of the elements and thus prevent them from moving inside the device.

Two multiplexers were employed. The multiplexers were used because the nine sensors have the same I2C address. The sensors are connected to the multiplexers and the multiplexers are connected to the shield that holds the Particle Photon. If a shield is not available, the cables from the multiplexers must be connected directly to the Particle Photon. At this point, the connection between the panel, the DFRobot solar power manager, and the battery must be made. Once all the devices are connected (sensors, multiplexers, Particle Photon, Panel, solar power manager, and battery), then the solar panel supports are attached (PanelSupport01 and PanelSupport02). These elements (panel supports) are attached to the BasePlate and allow the Solar Panel to be positioned above all the IoT hardware. In this way, the panel protects electronic devices from receiving direct sunlight and prevents them from heating up.
Now, each of the nine sensors should be attached to 3 elements: SensorSupportBottom, SensorFixer, and SensorSupportTop. The SensorSupportBottom is the element that is joined to the arches, the SensorFixer allows to set the height of the sensors so that it is not affected by the cable connectors, and finally the SensorSupportTop ensures that the light reaching the sensor is oriented perpendicularly with respect to the plane of the sensor. The proper order to couple the pieces are SensorSupportBottom, SensorFixer Sensor, and finally SensorSupportTop. Once the sensors are encapsulated, they can be attached to the arches (or semispheres), which in turn are assembled to the acrylic base, as can be seen in Fig. 1. Finally, the complete system is covered with the acrylic semisphere.

6. Operation instructions

To use the proposed device, you must first register on the Particle website. After this, it is necessary to download the Particle application, which allows you to configure the Photon WiFi Development Board so that it can receive user instructions. In addition, Particle has its own IDE available online (Particle Build IDE - https://build.particle.io/) to facilitate the code sending and editing. This online, browser-based IDE avoids installing any program on the PC, which is also an advantage for non-expert users. After sending the code to the Photon, WiFi credentials must be updated, either using the app mentioned above or using the console.

At this point you must choose the cloud service that will be used. In the market there are a wide variety of companies that provide this service, and in this case Ubidots was chosen. If the user prefers a different company, then it will be necessary to update some elements of the code and libraries according to the specific cloud service. For Ubidots, there is a unique token number for each user that must be updated before sending data to the Internet. Moreover, it is necessary to verify that in the compilation directives “ubienable” has a value of 1, in the case of other cloud services it must be 0. Finally, for the data to be transmitted through the serial port, “printenable” must be at 1.

Regarding the transmission of the data, the TLS2591 sensor delivers a visible radiation measurement and another global measurement with visible radiation plus infrared. Both values are sent to the cloud every two minutes. However, this time interval can be modified according to the user’s needs. Finally, it is important to mention that each sensor has a label to be identified when transmitting the information.

7. Validation and characterization

The operation of the proposed device was tested on the field, at a roof located in Medellín-Colombia, where a PV array is also in operation; the location of the experiments is described in Fig. 6. The PV system depicted in the figure has a peak power 1.3 kW, and it has instrumentation that provides voltage and current data, which is used for the device validation.

7.1. Data transmission and power consumption

The irradiance data was sampled each minute, in average, since the sampled time is controllable depending on both the power availability and data variability. In the device, the highest power consumption corresponds to the data transmission to
the cloud; therefore, the data transmission rate was limited to reduce the power consumption. Such a procedure was implemented by storing the irradiance data into the NVRAM of the MCU to be transmitted in four-samples packets; moreover, the WiFi module is disabled when the sensors data is acquired. Both strategies enable to save up to 70% of the energy in comparison with a non-optimized operation, i.e. transmitting one data in each cycle, and without disabling the WiFi module at the acquisition time. Fig. 7 presents an example of the current consumption for both modes, Mode₁ is the non-optimized operation, while Mode₂ is the optimized condition: the difference between the current consumption is caused by the time in which the WiFi module is turned on, this example shows the large energy saving achieved with the operation strategy adopted for the proposed device. In particular, T₁ and T₂ correspond to the time intervals in which the WiFi module is disabled and enabled for Mode₁, respectively; while T₃ and T₄ correspond to the time intervals in which the WiFi module is disabled and enabled for Mode₂, respectively.

7.2. Vectorial representation of the irradiance data

The sensors data are compressed in a vectorial representation to define the orientation of the maximum solar irradiance, which represents both the magnitude and incidence angle of the irradiance. Fig. 8 shows this concept using the sensors data recorded in Medellin-Colombia at 31-08-2019; where the black and cyan vectors represent the irradiance magnitude in each sensor at a given instant of time. Those vectors have a direction defined by the sensor position on the device; hence each sensor imposes the direction vector and magnitude, where that magnitude corresponds to the measured irradiance. In Fig. 8, the three-dimensional cartesian space is defined by the red, green, and blue axes; while the magenta vector S is the vectorial sum of the nine sensors vectors. Such a vector S provides the orientation and magnitude of the maximum solar irradiance at that particular location and time. To calculate the S value for a given period, e.g. a day, the vectors generated by the set of sensors are added using all the measurements along the period. Such information is useful to evaluate the effect of the irradiance incidence angle on the behavior of PV systems, which also helps to define the optimal orientation of the PV panel.

7.3. Experimental measurements

The proposed device was located so that the device axes coincide with the cardinal directions: the axis with sensors 1, 6, 0, 8 and 3 was oriented from east to west. The measurements were taken during two days, from August 31/2019 to September 01/2019, and those are reported in Figs. 9a, 9b, 10a and 10b. Moreover, Figs. 9a, 9b present the Hilbert transformation envelope of the experimental data to compensate for shading and irradiance variations, which are neglected for comparison purposes. The Hilbert transformation envelope is a waveform connecting the maximum values of a signal with high-frequency variations, thus filtering those high-frequency variations. In those figures, signal F₀ corresponds to the data from sensor 0, and signal eF₀ corresponds to the envelope calculated from signal F₀.

Figs. 9 and 9 show the measurements for sensors 0, 2, 4, 5, 6, 7 and 8 for August 31/2019. Fig. 9 shows that sensor 6, placed in a plane at 45° east, has the highest irradiance at morning when the sun light is perpendicular to that position. Similarly, the highest irradiance for sensor 0 occurs at noon since at that time the sun light is perpendicular. Finally, the highest irradiance in sensor 8 occurs in afternoon since that sensor is placed in a 45° west plane. Those measurements put into evidence the relation between the panel inclination angle and the power production, which could be used to calculate, accurately, the best inclination angle that guarantee the overall highest energy production along the day, or even, along the period in which the data is recorded (a week, a month, a year). Similarly, Fig. 9 presents the data from sensors 2, 4, 5 and
7, which are placed in south-north orientation. Such data enable to perform a 360° position analysis to define the best orientation and inclination of a PV panel depending on the irradiance incidence angle at each instant of time.

Fig. 10b shows the irradiance data obtained by the prototype for September 01/2019, which are in agreement with the data of August 31/2019 concerning the time in which the sensors exhibit the highest irradiance magnitude. However, in this new case (01–09-2019), Sensor 0 exhibits a much higher irradiance magnitude in comparison with the other sensors, which could be due to clouding conditions at both morning and afternoon, hence having a day with a higher irradiance at noon.
Fig. 10b shows the irradiance data captured by sensors 2, 4, 5 and 7 for the same day where, despite the irradiance increment observed in Fig. 10b, the sensors placed in the south-north orientation do not experiment a significant irradiance increment in comparison with the previous day.

7.4. Data comparison

The irradiance data provided by the proposed prototype is contrasted with the power generated by the PV installation located at the same rooftop used for the experimental test. The PV panels are installed at 0° with respect to the horizontal plane, which corresponds to the inclination of Sensor 0 of the proposed device. However, the PV panels are also affected by the diffuse components caused by other objects. Fig. 11a shows the power generated by the PV panels during August 31/2019, which is in agreement with the irradiance peaks observed in Fig. 9 for the morning, noon and afternoon hours; the current and power data of the PV panels were registered once per minute. Such a correlation confirms that the power generated by a PV panel is caused by the different irradiance levels occurring at different incidence angles; moreover, the data shows that the proposed device is a useful tool for defining the optimal inclination angle for the PV system. Finally, Fig. 11b shows the power generated by the PV panels during September 01/2019, which is also in agreement with the irradiance peaks observed in Fig. 10b.
7.5. Estimation of the optimal inclination angle

One of the main advantages of the proposed prototype, over geographical estimations, is the measurement of on-site conditions, which are difficult to simulate or estimate since, for example, new constructions could produce significant irradiance reflections. Then, using the aggregated irradiance vector, obtained from the vectorial sum of the nine sensors data described in Section 7.2, Figs. 12 and 13 show the resulting black vectors normalized for each instant of time along the day. The vectors have been normalized to enable a clear visualization of the maximum irradiance angle without accounting for the irradiance magnitude, and such an angle is in agreement with the sun movement for this particular experiment. However, in crowded urban environments, the irradiance reflected by buildings and other objects could produce a different optimal trajectory.

Using the vectors of maximum irradiance for each sampled time, the averaged maximum irradiance vector is calculated, which is depicted in magenta in both Figs. 12 and 13. Such a vector provides the optimal inclination angle for the PV panels located in that particular place during those particular days: for 31–08–2019, the spheric coordinates of that averaged vector are \( \theta = 1.0, \phi = 74.96 \), while for 01–09–2019 the averaged vector coordinates are \( \theta = 1.0, \phi = 85.29, \phi = 10.31 \). In those data, \( \theta \) represents the angle with respect to east–west plane, while \( \phi \) represents the inclination angle with respect to the horizontal plane.

Table 1 presents the normalized integral of the irradiance in each sensor of the proposed device for August 31 to September 05, 2019. Those values were obtained by integrating the irradiance curve of each sensor independently, then the data was normalized with respect to the maximum value obtained on the day. Therefore, in the table, the maximum irradiance for each day has a value of 1.0 highlighted in green. From those results is observed that the maximum irradiance was obtained mostly by sensor number 8, while sensor 0 is often in second place; hence those sensors produce the vectors closer to the optimal vector S, which is also reported in Table 1. For example, in September 01/2019 the maximum normalized value was obtained in Sensor 8, which is in agreement with Fig. 10b, where such a sensor receives a large amount of irradiance in the afternoon. Contrasting August 31/2019 and September 01/2019 it is observed that the latter one has higher irradiance values, i.e. a sunny day; moreover, at afternoons it is observed that Sensor 8 shows less changes on September 01/2019, which indicates a less cloudy day. The previous analysis is possible due to the large amount of data provided by the proposed device, which can be used to characterize a particular location in which a PV system will be installed.

Finally, the data of some of the sensors is stable for those days, which can be used to reconstruct the shading pattern caused by clouds or surrounding objects. Such an information can be used for reconfiguration purposes, which is another useful strategy to improve the power production of PV installations.

![Fig. 12. Higher irradiance vectors: 31-08-2019.](image-url)
In order to validate the proposed solution, a comparative simulation was performed in the System Advisor Model (SAM) software, which is commonly used for design and simulation of renewable energy generation systems. For this example it is considered a design of a 1.3 kW PV array connected to a grid-connected inverter; moreover, the SAM calculations are performed considering the irradiance measured in the real PV installation during the experiments described in the previous subsections, which will enable to validate the results provided by the proposed device.

The SAM software was used to simulate the PV power production for different inclination angles (Tilt angle) with respect to the horizontal axis, and for different orientation angles (Azimuth angle) with respect to the south-north plane; those simulations were used to validate the device results given in Table 1. The results of the SAM simulation are reported in Table 2, where the locations of sensors 0, 5, 6, 7 and 8 define the Tilt and Azimuth angles for the simulations; then the table reports the Annual Energy production (in kWh) predicted for the PV installation for those Tilt and Azimuth angles. Moreover, a SAM simulation for the optimal vector \( S \) \( [r = 1.0, \theta = 80.81, \phi = 8.70] \) was also conducted, which corresponds to \( Tilt = 8.70^\circ \) and \( Azimuth = 170.81^\circ \) in the PV installation.

### Table 1
Normalized integral of the irradiance.

| Vector S | 31-08 | 01-09 | 02-09 | 03-09 | 04-09 | 05-09 | Mean |
|----------|-------|-------|-------|-------|-------|-------|------|
| 0        | 1.00  | 1.00  | 1.00  | 1.00  | 1.00  | 1.00  | 1.00 |
| 1        | 0.22  | 0.15  | 0.46  | 0.36  | 0.30  | 0.35  | 0.33 |
| 2        | 0.26  | 0.14  | 0.26  | 0.49  | 0.35  | 0.22  | 0.31 |
| 3        | 0.33  | 0.26  | 0.29  | 0.37  | 0.51  | 0.37  | 0.38 |
| 4        | 0.23  | 0.14  | 0.22  | 0.43  | 0.17  | 0.18  | 0.25 |
| 5        | 0.44  | 0.27  | 0.48  | 0.59  | 0.43  | 0.43  | 0.47 |
| 6        | 0.60  | 0.50  | 0.58  | 0.63  | 0.69  | 0.52  | 0.61 |
| 7        | 0.52  | 0.31  | 0.42  | 0.59  | 0.32  | 0.48  | 0.47 |
| 8        | 0.79  | 1.00  | 1.00  | 0.78  | 1.00  | 1.00  | 1.00 |

### Fig. 13. Higher irradiance vectors: 01-09-2019.
Table 2 confirms that the highest energy production for the irradiance registered in 2019 occurs with the optimal Tilt and Azimuth angles defined by proposed device, which validates de measurements and analyses of the IoT device: PV installations configured with the optimal irradiance vector S will produce higher annual energy. The SAM simulations also shows that the second higher energy generation occurs with the Tilt and Azimuth angles of Sensor 0, hence the PV panels parallel to the horizontal axis; however, such a solution does not allow the air circulation around the panels, hence increasing the panels temperature, which could lead to overheating failures. In fact, that is the real orientation and inclination angle of the PV installation depicted in Fig. 6. The third highest energy production corresponds to the position of Sensor 6, in which the modules are located facing the east with an inclination of 45°, which is a viable configuration for a PV installation on a roof.

On the other hand, it is also noted that the SAM simulation for the angles of Sensor 8 (facing the west with an inclination of 45°) predicts a low annual energy, which is not in agreement with the data of Table 1 reported by the proposed device. Instead, in Table 1 the Sensor 8 reports a higher normalized integral of the irradiance in comparison with sensors 5, 6 and 0. Such a difference puts into evidence a significant advantage of the proposed device: the commercial design software (such as SAM) does not take into account the dynamic shading profile and reflective or diffuse irradiance caused by surrounding objects (such as windows), which could lead the software to disregard an orientation option that could produce high power under the real operation conditions of the particular installation. For the example of Sensor 8, the in situ experimental measurements provided by the IoT device report a high irradiance profile produced by the particular conditions of the location, which will be translated in a high power production; however, the SAM simulation is not able to take into account those real conditions.

This example shows the applicability of this IoT device to define the optimal locations for PV installations in urban environments, where the panels could be exposed to different shading patterns, or to diffuse and reflective irradiance caused by surrounding objects, which are complex conditions difficult to predict using software packages such as SAM. Another application for the IoT device concerns the interaction with a mechanical tracking system for PV arrays, which could enable the tracking system to follow the sun and avoid deep shading conditions using the IoT device data in real-time, thus improving the energy generation of the PV installation.

Some features and limitations of the device are summarized as follows:

- The IoT characteristics enable the real-time data acquisition, which can be used for improving sun tracking systems; moreover, the device operation can be adjusted depending on the data variability (resolution and sampling time) to reduce power consumption.
- The irradiance measured by each of the nine sensors is normal to the sensor plane, hence it is a directional measurement. Such a characteristic enables to calculate the optimal incidence angle with high precision.
- The device is designed with low-cost elements, hence the overall cost of the proposed solution is lower than the cost of a commercial pyranometer.
- The operation time of the device depends on the energy stored in the battery, thus it requires enough solar irradiance to charge the battery for a full cycle. However, under raining conditions, the battery could be discharged, and the device will be out-of-operation until a minimum battery charge is restored.
- The device can only be programmed using the Particle IDE. This online IDE is ideal for non-expert users, since it does not require the installation of any program on your PC.

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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References

[1] E. Romero-Cadaval, G. Spagnuolo, L. García Franquelo, C. Ramos-Paja, T. Suntio, W. Xiao, Grid-connected photovoltaic generation plants: Components and operation, IEEE Ind. Electron. Mag. 7 (3) (2013) 6–20, https://doi.org/10.1109/MIE.2013.2264540.
[2] G. Petrone, C.A. Ramos-Paja, G. Spagnuolo Sources Modeling, Wiley-IEEE Press (2016).
[3] L. Herrera, A. Miranda, E.I. Arango, C.A. Ramos-Paja, D. González, Dimensionamiento de sistemas de generación fotovoltaicos localizados en la ciudad de medellín, Tecnolóxicas (2013) 289–301.
[4] J.S. Botero-Valencia, S. Kang, J.T. Kim, Optimization of the building integrated photovoltaic system in office buildings-focus on the orientation, inclined angle and installed area, Energy Build. 46 (2012) 92–104, sustainable and healthy buildings. doi: 10.1016/j.enbuild.2011.10.041.
[5] G. Li, J. Tang, R. Tang, Performance and design optimization of a one-axis multiple positions sun-tracked v-trough for photovoltaic applications, Energies 12 (6) (2019) 1141, https://doi.org/10.3390/en12061141.
[6] J.D. Mondol, Y.G. Yohanis, B. Norton, The impact of array inclination and orientation on the performance of a grid-connected photovoltaic system, Renew. Energy 32 (1) (2007) 118–140, https://doi.org/10.1016/j.renene.2006.05.006.
[7] P. Nepal, M. Korevaar, H. Ziar, O. Isabella, M. Zeman, Accurate soiling ratio determination with incident angle modifier for pv modules, IEEE J. Photovoltaics 9 (1) (2019) 295–301, https://doi.org/10.1109/JPHOTOV.2018.2882468.
[8] T. Rodziewicz, J. Nakata, K. Taïra, A. Zaremba, M. Wactawek, Impact of the solar irradiation angle on the work of modules with spherical cells - simulation, Ecol. Chem. Eng. Sci. 25 (1) (2018) 35–50, https://doi.org/10.1515/ecs-2018-0002.
[9] G. Spagnuolo, G. Petrone, B. Lehman, C. Ramos-Paja, V. Zhao, M. Orozco Gutierrez, Control of photovoltaic arrays: Dynamical reconfiguration for fighting mismatched conditions and meeting load requests, IEEE Ind. Electron. Mag. 9 (1) (2015) 62–76, https://doi.org/10.1109/MIE.2014.2360721.
[10] S.Y. Alsadi, Y.F. Nassar, A general expression for the shadow geometry for fixed mode horizontal, step-like structure and inclined solar fields, Solar Energy 181 (2019) 53–69, https://doi.org/10.1016/j.solener.2019.01.090.
[11] Y. Ota, T. Masuda, K. Araki, M. Yamaguchi, A mobile multipyranometer array for the assessment of solar irradiance incident on a photovoltaic-powered vehicle, Solar Energy 184 (2019) 84–90, https://doi.org/10.1016/j.solener.2019.03.084.
[12] J.P.d.C. da Costa, R.H. Gounella, W.B. Bastos, J.P. Carmo, Photovoltaic sub-module with optical sensor for angular measurements of incident light, IEEE Sens. J. 19 (8) (2019) 3111–3120, https://doi.org/10.1109/JSEN.2019.2891307.
[13] A. Crespo, A. Alonso, Una panorámica de los sistemas de tiempo real, Revista Iberoamericana de Automática e Informática industrial 3 (2) (2006) 7–18.
[14] D. Martínez, P. Balbastre, F. Blanes, J. Simó, A. Crespo, Procedimiento de diseño para maximizar el consumo de potencia y los retrasos en wsn, Revista Iberoamericana de Automática e Informática industrial 7 (3) (2010) 95–110.
[15] A.F. Prieto, O. Llanes-Santiago, Núcleo de control para sistemas empotrados de control: Una propuesta de arquitectura, Revista Iberoamericana de Automática e Informática industrial 8 (1) (2011) 64–79.
[16] J. Ortega, M. Sigut, Prototipo de una plataforma móvil de bajo coste para simulación de vuelo de alto realismo, Revista Iberoamericana de Automática e Informática industrial 13 (2016) 293–303.
[17] M. Castrillón-Santana, J. Lorenzo-Navarro, D. Hernández-Sosa, Conteo de personas con un sensor rgbd comercial, Revista Iberoamericana de Automática e Informática industrial 11 (X) (2014) 348–357.
[18] KNIPZONEN, Smp 22 pyranometer (2020). URL: https://www.kippzonen.es/Product/360/SMP22-Pyranometer#.X2N_BmhKiM8.
[19] Hukseflux, Hukseflux pyranometer (2020). URL: https://www.hukseflux.com/products/solar-radiation-sensors/pyranometers.
[20] A. Takalate, S. Harrouni, M.A. Yaiche, L. Mora-López, New approach to estimate 5-min global solar irradiation data on tilted planes from horizontal measurement, Renew. Energy 145 (2020) 2477–2488, https://doi.org/10.1016/j.renene.2019.07.165, URL: https://linkinghub.elsevier.com/retrieve/pii/S0960181119311851.
[21] S. Halliovic, J.M. Bright, W. Herzberg, S. Killinger, An analytical approach for estimating the global horizontal from the global tilted irradiance, Solar Energy 188 (June) (2019) 1042–1055, https://doi.org/10.1016/j.solener.2019.06.027.
[22] J. Polo, S. García-Boubaben, M.C. Alonso-García, A comparative study of the impact of horizontal-to-tilted solar irradiance conversion in modelling small PV array performance, J. Renew. Sustain. Energy 8(5), doi: 10.1063/1.4964636.
[23] C.F. Abe, J.B. Dias, G. Notton, G.A. Faggianelli, Experimental application of methods to compute solar irradiance and cell temperature of photovoltaic modules, Sensors (Switzerland) 2009, doi:10.3390/s20092490.
[24] DeltaOhm, LPPYRA02 (2020). URL: https://www.deltaohm.com/en/product/lppyra02-serie-first-class-pyranometer/.
[25] AMS, TS12591 (2019). URL: https://ams.com/ts12591.
[26] DFROBOT, DFRobot 2019 (2019). URL: https://wiki.dfrobot.com.
[27] X. Yang, N. Li, Y. Heng, X. Qian, X. Ma, Y. Tang, J. Xiao, G. Zhang, W. Cheng, H. Song, M. Li, Z. Cai, K. Huang, Z. Wu, W. He, Y. Pei, Study on acrylic transmittance for JUNO Central Detector, Rad. Detection Technol. Methods 5 (2) (2021) 284–289, https://doi.org/10.1007/s41605-021-00242-z.
[28] DFRobot, DFRobot 2019 (2019). URL: https://wiki.dfrobot.com.
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