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Design of an accurate, low-cost autonomous data logger for PV system monitoring using Arduino™ that complies with IEC standards

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ABSTRACT

A new data logger using the Arduino open-source electronic platform was developed to solve the current problem of monitoring photovoltaic (PV) systems at low-cost, especially in remote areas or regions in developing countries. The data logger meets all of the relevant requirements in terms of accuracy included in the International Electrotechnical Commission (IEC) standards for PV systems, with a resolution of 18-bits, including 8 analogue inputs for measuring up to 8 PV modules and/or weather sensors, 3 inputs for low-cost analogue temperature sensors and virtually unlimited inputs for digital temperature sensors. The new data logger is completely autonomous, and the prototype has achieved an initial cost of only 60 €. It was tested during a 6-month period under the harsh environmental conditions of the summer and winter in Southern Spain. The results using both the sensors and silicon reference cells indicate that the new system is reliable and exhibits comparable performance to commercial systems. This data logger is of special interest for both solar energy research and applications in developing countries, as it is both open-source and flexible. The data logger can be customised for the specific needs of each project at low-cost. The details of the specific design and its implementation are described.

1. Introduction

PV monitoring systems usually require a vast number of parameters to be recorded: temperatures, irradiances, voltages, currents, etc. Such PV monitoring systems are used in research applications that require the monitoring of all cell temperatures of a PV module or in PV installations requiring multiple monitoring systems for an extended network, such as in a number of small solar home systems or medium-size PV plants in developing countries. However, the data collecting devices, commonly known as data loggers, are too expensive, demand special software (with increased cost and requiring additional specific skills), and require a power supply or a PC to be connected all of the time. In addition, typical data loggers do not match the type of sensors to be measured well with regard to accuracy, insufficient number of input channels, or inadequate input channels for the connection of specific sensors, such as in the case of thermocouples or digital sensors. These problems and limitations, both in terms of cost and technological capabilities, led us to design and develop a new data logger capable of monitoring PV systems at low-cost and with a flexible design. The main objective was to develop a data logger with the following characteristics: (a) low-cost, using easily obtained hardware and free software; (b) autonomous operation with low energy consumption and not dependent on a computer or access to a power grid; (c) easy-to-build and handle; (d) high accuracy and meeting International Electrotechnical Commission (IEC) standards (specifically IEC61724 [1] and its normative references); (e) efficient data acquisition; (f) data-file creation capability; (g) robust when used in a harsh environment (i.e., outdoors); and (h) flexibility to be easily adapted to different PV applications by implementing a few changes (for example, allowing the number and type of input channels to be modified).

1.1. Prior work on data loggers for PV monitoring

The fast evolution of renewable energy technologies during the last several years has led to the installation of many systems all over the world. However, most of these technologies have not yet achieved full-development. The costs of renewable energy technologies have not yet

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dropped sufficiently so that grid parity is universally achieved without subsidies. There is still a margin for technology improvement and cost reduction. In the particular case of photovoltaic systems, detailed knowledge of the meteorological data for the location where the system will be installed is desirable, as well as a full monitoring of the PV system performance [2]. On the one hand, it is possible to find reliable meteorological data for a given location due to data collected by National or European institutions [3–5]; this information can be used to obtain general knowledge of the conditions, but this cannot replace the specific data taken on-site. On the other hand, there are many locations where these databases are not available or they are in the process of being collected. A wide range of commercial data loggers for climate monitoring is available, but they are expensive, highly sophisticated and cannot be easily managed. As a result, further development of data-acquisition systems is required to collect and process such meteorological data in addition to monitoring the performance of PV systems under operation, under the premise of obtaining the measured parameters using accurate, easy-to-handle and low-cost systems.

The literature includes numerous reports of such systems during the last several years. One of the first systems developed for on-site measurements of PV array characteristics and PV monitoring systems, enabling the collection, analysis and presentation of operational data, was conducted by Blaesser [2], where the data acquisition equipment was rather expensive (over 10% of the system cost). Because the prices for data acquisition hardware have decreased more rapidly than the prices of PV systems, analytical monitoring has been gradually applied to small PV installations. One of the first attempts to design low-cost hardware for solar radiation monitoring and then for environmental monitoring was developed by Mukaro et al. [6] and [7]. The system was designed around an 8-bit microcontroller that managed an analogue-digital converter (ADC) and stored data in a serial EEPROM until uploaded to a portable computer. Because of an improvement stage, 4 analogue inputs were available under limited uncertainty. The data were sampled and stored in 10-min intervals; and the power consumption was minimised by keeping the microcontroller in a low-power mode between intervals because the data acquisition system was powered by a rechargeable battery. This system was well suited for monitoring meteorological or environmental parameters at remote stations, particularly in developing countries, and one of its subsequent uses was analysed in Mukaro and Tinarwo [8]. One operator with one laptop is all that was required to collect the acquired data from the systems scattered around an area of interest. Another effort to develop an integrated data-acquisition system for renewable energy sources was reported by Koutroulis and Kalaitzakis [9]. The main disadvantages of this system were the dependence on a PC, the use of commercial software (Labview™), and the requirement of a power grid supply, which increased the price of the system and limited its spread and use. More designs based on microcontrollers can be found in the literature, but some of them use a low resolution ADC attached to an amplifier stage, which defines every input to a specific sensor [10,11], while others depend on a PC [11–14], commercial software [15,16], or do not follow IEC standards to manage accuracy or obtain data, which offset the achievement of low cost, portability and low power consumption, among other advantages [17,18].

With this background and under the current technical development, our approach for a low-cost data logger serves different basic purposes, as mentioned earlier, e.g., because it is supported by free hardware and software, its design is accessible to everybody. This public access facilitates rapid and continuous development. In addition, due to the flexibility of adapting the new data logger design for PV monitoring to each specific case (both research and industrial applications in developed and developing regions), the proposed data logger can enable the PV community to advance faster in some of the research areas that have been in need of full PV monitoring but have been limited by cost and technology issues.

This paper presents the design of the novel low-cost data logger for PV monitoring, discussing first the fundamentals of portable data acquisition in photovoltaic systems and reviewing the main photovoltaic parameters that must be measured, with special emphasis on their accuracy or uncertainties under the IEC61724 standard. The design of the data logger is then presented, including the modular diagram configuration offered by the use of free software and hardware, i.e., a microcontroller unit (MCU) and modules of acquisition, storage, etc., and all of the components used in the manufacturing of the data logger are described thoroughly. Next, the initial characterisation results, including a comparison with the results from a commercial system and the IEC tests, are shown in the electronic Supplementary Materials attached to this manuscript. The testing period performance (over 6 months) under harsh environmental conditions is discussed with different experimental setups, specifically calibrating the PV cells, monitoring a stand-alone PV system, and monitoring a small grid-connected PV system. Finally, a cost analysis and the amount of energy consumption of the data logger are presented.

2. Portable data acquisition requirements in photovoltaic systems

Portable data acquisition applications must meet a number of strict requirements that are not present in traditional laboratory systems. These systems are used in harsh environments that must be considered when selecting this type of equipment, such as extreme temperatures, humidity, dust, shock and vibration. For example, in photovoltaic applications, equipment must withstand temperature ranges that vary between -40 °C and $+85$ °C for PV modules in the worst case [19]. Other concerns include whether this equipment is capable of supporting the mix of the particular sensors that will be used, as well as if there is adequate memory/storage to support the test. Invariably, the accuracy of field measurements is highly dependent upon the sensors being used. For most sensors that have been calibrated in the laboratory and installed in the field, accuracies in the range of 0.01–1% of full scale are typical. Signal conditioning, such as gain and filtering, and the data acquisition sampling speed are other important considerations when determining the accuracy of the system.

Ideally, remote data acquisition systems are typically stand-alone instruments that, once they are set-up, can measure, record and display data without operator or computer intervention. These systems are able to receive data from multiple inputs, feature built-in signal conditioning and can simultaneously record data from a variety of different sensors. These systems must be compact, light-weight units that can be powered using two different configurations. The first is using a battery pack, and the second is to run an external wire to a DC power supply. To conserve power, users with minimal processing requirements can select a lower range processor and pair it with a high-end storage system to prevent the selection of a processor with capabilities beyond those that are necessary. These systems are left to operate unattended for days or possibly years at a time and can have communication capabilities using telephone connection or wireless systems for downloading data to remote computers, large amounts of built-in storage, and user interfaces for remote setup and control of the device.

These powerful yet compact data acquisition devices play an important role in the verification testing and monitoring of critical systems, and selecting the appropriate device for a given application requires careful consideration. In our case, the design will be

Table 1
Parameters to be measured in real time in photovoltaic systems.

General parameter	Specific parameter	Symbol
Meteorology	• Total irradiance, in the plane of the array (Direct+Diffused) • Ambient temperature in a radiation shield • Air speed and direction (optional)	G_I (DHI DNI) T_{am} S_W
Photovoltaic array	• Output voltage • Output current • Output power • Module temperature • Tracker tilt angle (optional) • Tracker azimuth angle (optional)	V_A I_A P_A T_m Φ_T Φ_A
Energy storage	• Operating voltage • Current to storage[a] • Current from storage[a] • Power to storage[a] • Power from storage[a]	V_S I_{TS} I_{FS} P_{TS} P_{FS}
Load	• Load voltage • Load current • Load power	V_L I_L P_L
Utility grid	• Utility voltage • Current to utility grid[a] • Current from utility grid[a] • Power to utility grid[a] • Power from utility grid[a]	V_u I_{TU} I_{FU} P_{TU} P_{FU}
Back-up sources	• Output voltage • Output current • Output power	V_{BU} I_{BU} P_{BU}

[a] A single current or power sensor can be used for the measurement of current or power for directions of both input and output.

supported by a low-cost processor, whose limitations will be addressed by different devices that comply with the previously mentioned objectives, as well as with IEC requirements, without increasing the price significantly.

2.1. Critical parameters to be monitored in a photovoltaic system

In general, a photovoltaic system integrates solar modules, batteries and regulators for the case of stand-alone systems, inverters for the case of grid connection, AC and DC wiring, electrical security devices, and protection devices. International standards set the parameters that must be measured and monitored. Specifically, the IEC61724 standard titled "Photovoltaic system performance monitoring – guidelines for measurement data exchange and analysis" describes the general guidelines for the monitoring and analysis of the electrical performance of photovoltaic systems [1]. Table 1 presents a summary of such parameters.

An example of applying the IEC61724 standard for a general photovoltaic system is depicted in Fig. 1, and the particular case for stand-alone photovoltaic systems is shown in Fig. 2.

In both cases, the number of measurements can be reduced if the current sensors can distinguish its direction. So, without the optional parameters, 13 variables must be measured in the general diagram described in Table 1 (2 temperatures, 1 irradiance, 5 voltages, 3 directional currents, and 2 bidirectional currents) and 9 in the specific case of stand-alone photovoltaic systems (2 temperatures, 1 irradiance, 3 voltages, 2 directional currents, and 1 bidirectional current). An important starting point is to determine the number of inputs of the design of the data logger.

2.2. Accuracy of the photovoltaic parameters

Designing a device that meets the IEC standards is one of the main objectives of this work. The sections that follow describe the different PV measurements, dividing them depending on the magnitude and range, and the accuracy requirements for each one of them are specified.

2.2.1. Measurement of irradiance

The in-plane irradiance will be measured in the same plane as the photovoltaic array by means of the calibrated reference devices or pyranometers [19]. This work also attempts to use low-cost sensors by using reference cells or small modules that will be calibrated and maintained following the IEC standards IEC60904-2 [20] and IEC60904-6 [21]. The location of these sensors will be representative of the irradiance conditions of the array; in addition, their accuracy, including signal conditioning, must be better than 5% of the reading. For practical reasons, reference cells must be shunted by a precision resistor to avoid the case where users can establish the short circuit condition. In such cases, the precision resistor should be selected so it ensures that the reference device operates sufficiently near the short-circuit condition, thus meeting the requirement:

$$I_{SC} \times R_{CAL} < 0.03 \times V_{OC} \tag{1}$$

where:

R_{CAL} is the precision shunt resistor;
I_{SC} is the short circuit current of the reference device at reference conditions;
V_{OC} is the open circuit voltage at reference conditions.

The long-term stability of such resistors must also meet the stability requirements of the reference sensor. The calibration values of such reference cells are stated in units of [V/W m^{-2}] if the calibration was performed on the voltage drop across the shunt resistor. In addition, the shunt temperature coefficient of resistance (TRC) is usually expressed in units of ppm/°C (parts per million per centigrade degree) and indicates how much its value changes as its temperature changes. Precision resistors have a TCR under 30 ppm/°C. Therefore, the data logger design has to be sufficiently accurate to measure voltage below 5% of the reading of irradiance from the relationship between the irradiance and the voltage.

2.2.2. Measurement of temperature

The ambient air and PV module temperatures are measured at a location that is representative of the array conditions, using temperature sensors located in the solar radiation sensors for the former case and on the back surface of one or more modules for the latter. The accuracy of these temperature sensors, including signal conditioning, must be better than 1 °C. To determine the temperature of the reference cell or the reference modules, the equivalent cell temperature (ECT) can be obtained by measuring V_{OC} at a level of accuracy below $\pm$0.5% according to IEC60904-5 [22]. However, to comply with this standard, it is necessary to know the cell voltage temperature coefficient (β) or to determine it from the method described in IEC60891 [23] by making the comparison between V_{OC} and the temperature sensor located on the back surface of the PV device and using the minimum-squares fit method. In this case, the temperature sensor measurement must have an accuracy of $\pm$0.5 °C.

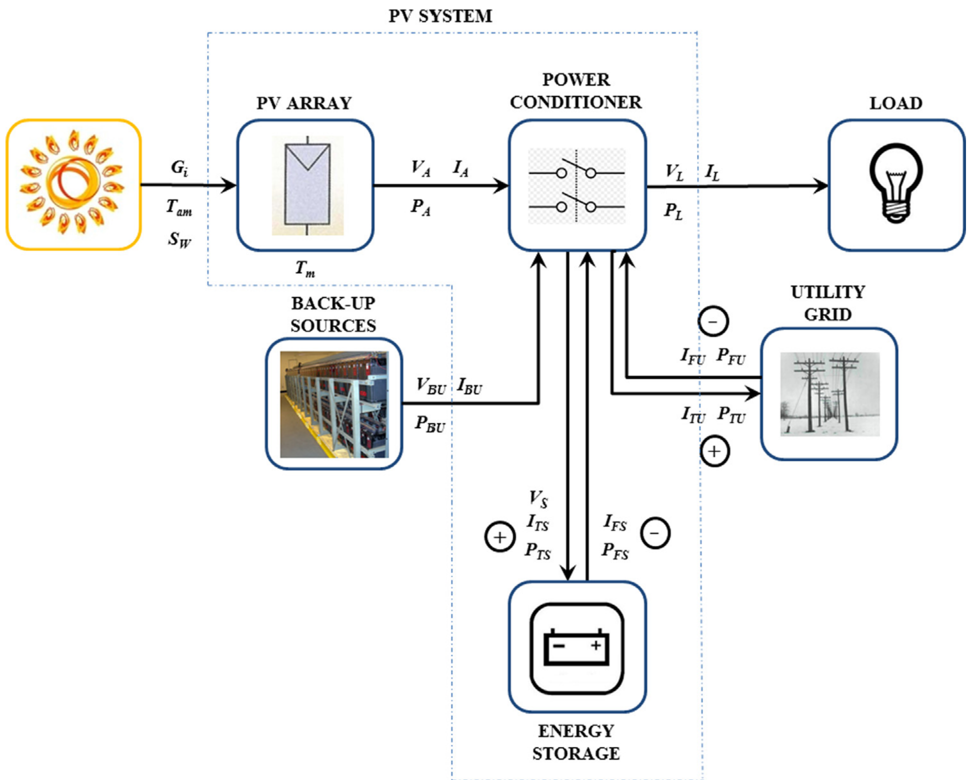

Fig. 1. General diagram of the parameters to be measured in real time in a photovoltaic system [1].

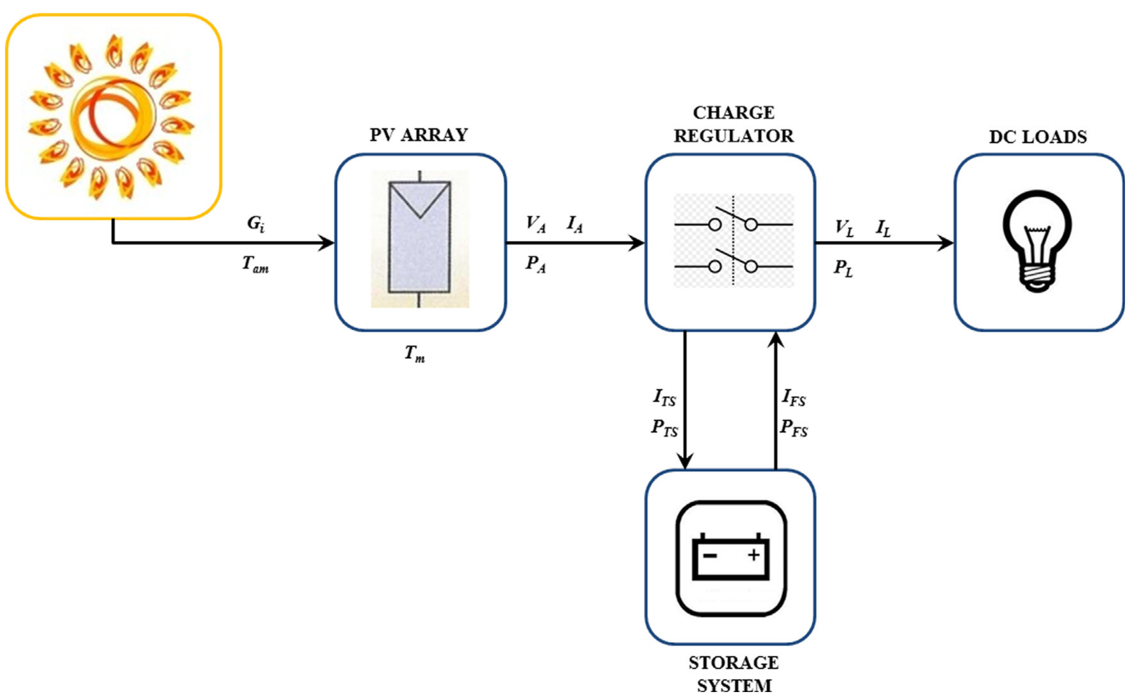

Fig. 2. Specific diagram of the parameters measured in real time for stand-alone PV systems [1].

In addition, if the PV sensors are operating in open circuit voltage, measuring the irradiance -proportional to current- or its output power would not be possible; as a result, the use of temperature sensors attached to the back of the reference devices is required, but the cell back-skin temperatures must also be corrected to the effective cell temperatures by adding 2.5 °C with a total range of ± 1 °C [24,25] depending on the back surface utilised in the sensor manufacturing.

2.2.3. Measurement of the voltage, current and power

The voltage and current parameters may be either direct current (DC) or alternating current (AC). The accuracy of the voltage and current sensors, including signal conditioning, must be better than 1% of the reading. The AC voltage and current may not need to be monitored in every situation. The two main methods to measure current consist of using shunts or current transducers. The use of shunts is very simple and does not require an extra power supply but does require a high sample rate monitoring for measuring AC. The use of current transducers requires a power supply and can measure both AC and DC. The price for both methods depends on their accuracy and range, which requires an in-depth study to determine the price for each case. Similarly, the voltage transducer or voltage dividers can be used to measure the DC voltage. The cost will be higher for the voltage transducer, but both require an accuracy assessment. In the case of AC voltage, voltage transducers are required, unless the data logger is prepared to accept AC signals.

The electrical power parameters may be DC or AC or both. The DC power can either be calculated in real time as the product of the sampled voltage and the current quantities or measured directly using a power sensor. If the DC power is calculated, the calculations must use the sampled voltage and current quantities and not the averaged voltage and current quantities because the average depends on the sample rate and errors can be significant for large current variations. The AC power must be measured using a power sensor that properly accounts for the power factor and harmonic distortion. This energy metre usually contains a voltage and a current transducer. The accuracy of power sensors, including signal conditioning, must be better than 2% of the reading.

3. New low-cost portable data logger: hardware and software

The new low-cost portable data logger is presented in this section, including both hardware and software. A complete diagram of the concept is shown in Fig. 3. The microprocessor board manages the other boards, temperature sensors, current sensors and PC communication by utilising several data protocols.

3.1. Selection of a low-cost processor

The first premise of the novel data logger is the use of free software and hardware. This premise is necessary to achieve the low-cost objective of the final system and make it suitable for developing countries or research applications that must use these devices. Within the numerous platforms based on microcontrollers that are available in the market, MSP430 launch Pad, STM8L Discovery, Waspmote from Libelium and Arduino UNO are well known among developers [26–29].

The prices for the microcontrollers are below 10 € for Texas Instruments and STMicroelectronics. Waspmote is the most expensive (135 €) and is nearly inaccessible to developers. Arduino stands out due to the simplicity of its hardware (easily duplicated without expensive means) and software (with numerous web pages and forums on the Internet providing a lot of information, libraries and examples for its customers) in comparison with the other three. Arduino UNO has easy handling and learning together with the numerous web pages containing support, examples, libraries, and many modules for adapting designs to new specifications. The modularity of Arduino UNO is guaranteed, finding a wide range of modules to interconnect for adapting the platform to any design, such as Bluetooth, Wi-Fi, LAN, GPS, GPRS, etc., or the possibility to develop new modules with a specific purpose [30–33]. These characteristics are not common to all platforms. Some of the platforms are less expensive, but it is very difficult to find support, libraries or modules for such platforms, and it is necessary to develop all of the programs starting from scratch. This required development causes users to relinquish projects because of the trade-off between the results and the dedicated effort.

Arduino UNO is a basic microcontroller that is comparable in price to the least expensive ones (16 €), but it is very easy to adapt any design due to the advantages mentioned above. Therefore, Arduino UNO was selected considering that, both for research and in developing countries, people may want to improve and adapt the data logger to their own designs. The printed circuit board (PCB) can be built manually or purchased preassembled; in addition, the software can be downloaded for free. The hardware reference designs are available under an open-source licence, and the users are free to adapt them to their needs. The hardware is based on ATmega328 microcontroller and has 14 digital input/output pins, 6 analogue inputs, a power jack and a USB connection among its main characteristics. The board contains everything required to support the microcontroller. The board can operate using an external supply (USB cable, AC/DC adaptor or a battery) of 6 V to 20 V; however, it is recommended to operate the board in a range from 7 V to 14 V to avoid the board becoming unstable or the voltage regulator overheating and damaging the board [29]. The design offers its own sleep mode to significantly reduce the power consumption [34].

Arduino UNO has 6 analogue inputs with an ADC of 10-bit resolution. The ADC has an input range of 5 V, but it can be changed by hardware with a new voltage reference in pin AREF (up to 0.5 V) or by software up to 1.1 V. In the case of 1.1 V voltage reference, this configuration can measure 2^{10} or 1024 voltage levels, and the step would be 1.07 mV. This resolution is sufficient for many applications, i.e., for research and development applications on small cells or modules for short periods of time and for reading from low-cost analogue temperature sensors with good accuracy; however, this resolution is not appropriate for meeting

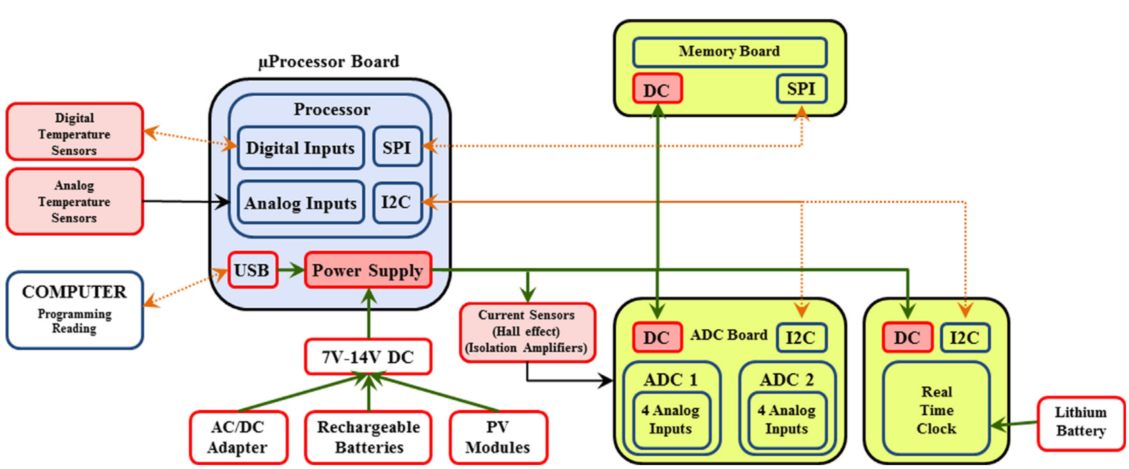

Fig. 3. Detail of the new data logger modularity: the main module is the microprocessor board, composed of Arduino UNO, which can manage the rest of the modules using different bus protocols: temperature sensors, current sensors, analogue-digital converter boards, a real-time clock, storage modules, and future improvements, such as Bluetooth, LAN or GPRS modules. The computer is only required to load the programme during its design and to read the collected data.

all of the requirements of the IEC61724 standard because irradiance sensors, for example, have resolutions below hundreds of microvolts. Moreover, the minimum number of parameters to be measured and monitored was 9, while Arduino UNO only has 6 analogue inputs.

The EEPROM memory capacity of Arduino UNO is limited to 1 kilobyte (kB), which is insufficient to store data or files over a monitoring period (9 parameters stored each minute would exceed 1 kB in 6 min); however, there are many expansion modules for memory sticks, each with a capacity of up to 2 gigabytes (GB). Arduino UNO does not count on the presence of a Real-Time Clock (RTC), which would allow the system to keep track of the time in spite of shortages of power supply. However, Arduino UNO has I²C™ (multimaster serial single-ended computer bus) and SPI (serial peripheral interface bus) buses to communicate with almost everything, using protocols previously implemented for every device. In this work, pins A5 and A4 are used for the I²C™ bus, and pins 10, 11, 12 and 13 are used for the SPI bus.

3.2. Hardware improvement

Regarding all of the problems presented by Arduino to meet the IEC standards, the acquisition of the produced modules or the development of the new ones should be the best solution. As a result, we developed a printed circuit board (PCB) choosing an analogue-digital converter (ADC) of 18-bit resolution, specifically MCP3424 from Microchip™, which has four differential channels with an input range of ± 2.048 V, high accuracy (up to 2 μV) and uses a two-wire I²C™ bus to transmit the data. Finally, two ADCs were included in the PCB to monitor up to 8 analogue inputs and satisfy the requirements in the diagrams shown in Figs. 1 and 2. Following the same standard criteria, the possibility of connecting some voltage dividers was designed to optionally increase the input range of the ADC from ± 2.048 V up to $+96$ V, in case it is necessary. Common-mode voltage precision difference amplifiers (AD8479, INA117, or similar) were added to one of the ADCs to avoid damage to their analogue inputs when high voltage current sensing derives from PV systems. Another solution would be to use Hall-effect sensors to measure current with the ADC directly; however, in this case, its cost could be high and the accuracy low for medium-high currents. The DS1307 serial RTC was selected to avoid losing the time base in case of a lack of power supply because Arduino UNO does not have a means to store the time when the data are recorded. This DS1307 uses the I²C™ bus and is integrated in the same PCB design to save space, money and the number of electronic interconnections. The board design process is depicted in Fig. 4.

It is necessary to keep all of the data collected in files organised by dates according to IEC61724 [1]. Due to the small capacity of the internal EEPROM of the Arduino UNO board, one piled module was chosen for its price-characteristics relationship. Specifically, a 2 GB SD flash memory was chosen, which has high storage density, rapid speeds of reading and writing, and low-cost and is based on an SPI bus.

Regarding the temperature measurements, the sensors can be either analogue or digital. Analogue measurements require a constant DC supply in addition to good accuracy to obtain data with a low uncertainty. In addition, each sensor requires an independent cable of up to 4 wires, depending on the sensor type: thermistor, PT-100,

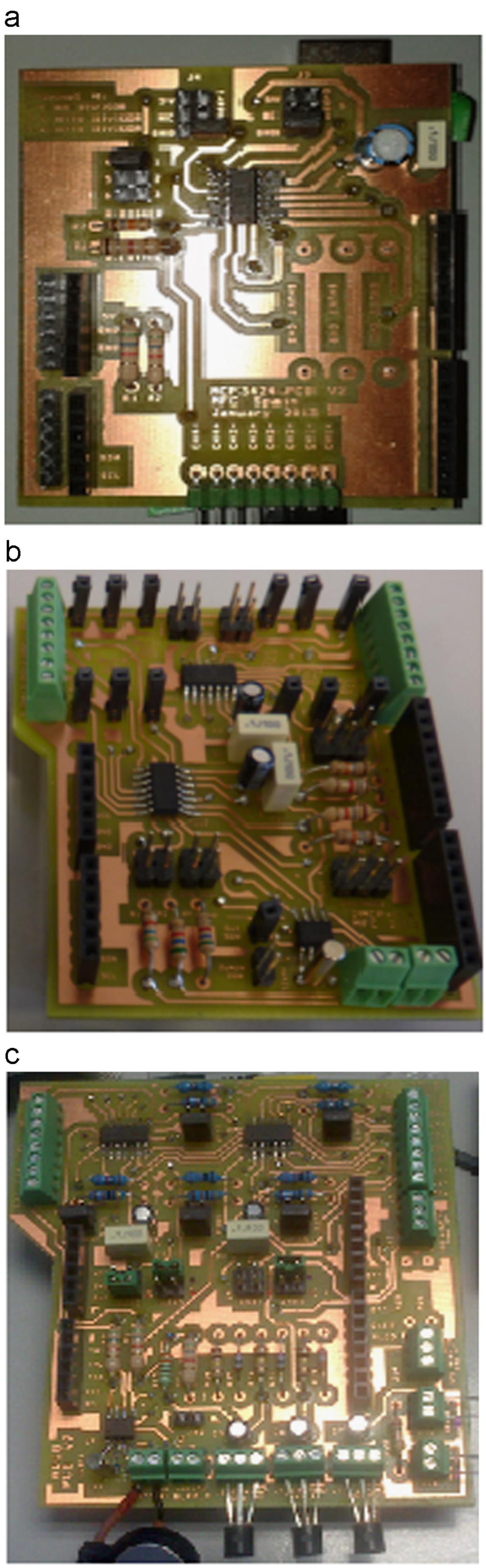

Fig. 4. (a) Development of the first stacked board with Arduino UNO dimensions and one MCP3424 ADC chip. In this way, the user can control four ADCs using one I²C™ bus. **(b)** Development of the first prototype with two MCP3424 chips and one real-time clock DS1307. The board is prepared to host up to 6 small shunts to measure currents below 2.5 A. In addition, the board is stacked and relies on two inputs with voltage dividers to measure higher voltages. It is only necessary to locate jumpers in the fixed positions. (c) The second stacked prototype that improves on the first prototype by using five voltage dividers and having a location for connecting three low-cost analogue temperature sensors (LM35) and one-wire protocol implemented for digital temperature sensors (DS18B20).

LM35, etc. In the case of digital sensors, there are low-cost devices exhibiting an accuracy that satisfies the IEC61724 standard that only uses one cable of tree wires for all them. Thus, the DS18B20 (with an accuracy of ± 0.5 °C between -10 °C/$+85$ °C), communicates over a One-Wire protocol. Because each device has a unique code, the number of devices that could be addressed on one bus (one digital input) would be virtually unlimited, leaving the analogue inputs free for other sensors. Both possibilities were implemented in the same PCB, as shown in Fig. 4c.

3.3. Software design

Arduino has its own open source programing language based on C/C^{++}. The software developed for the data logger was very simple: no interaction with the users was taken into account for its operation time to guarantee its robustness. The only interface consists of one green LED, which will switch on for a few seconds in a cyclical way every time the data are recorded, indicating that the software runs properly. If any problem occurs, the LED will switch on continuously. As the IEC61724 standard advises sampling intervals below 1 min for parameters related to irradiance, 30 s was the interval chosen, coinciding with second 0 and second 30 of every minute. The programme will adapt easily to new variables when the hardware, channels, or time interval change. Following the same standard, the files for a full day will be recorded in plain text archives, written in single-byte ASCII code. In this way, the files are largely immune to computer architecture incompatibilities and facilitate the exchange of data between organisations. For the last prototype, the first field is the hour in the format *hh:mm:ss*. The next eight columns represent the eight differential inputs from the ADC expressed in mV. The following three fields represent the low-cost analogue temperature expressed in °C. After the analogue temperature, six columns of digital temperature expressed in °C appear. The two last columns represent the inner temperature of the microcontroller (in °C) and its power supply voltage in volts.

3.4. Assembled prototype

The design was based on the Arduino UNO board. The only user interface consisted of one green LED, whose operating mode was described in section 3.3. No displays were taken into account in the design for three reasons: reduce costs, reduce power consumption, and simplify the software and hardware design.

The last ADC PCB design included two ADC chips to measure eight differential inputs, five of them with voltage dividers to measure high voltages (up to 96 V, in case these measurements were required); three inputs (with passive components suggested by the manufacturer for long distance cables) for LM35 analogue temperature sensors; one connector with one-wire bus for DS18B20 digital temperature sensors; the real-time clock DS1307; and a 5 V supply connector for the external modules. The LM35 sensors were not used after testing them because of their interferences and, consequently, lack of accuracy when long cables were used to fix them in PV installations (despite following the manufacturer's instructions for these cases). Nevertheless, the connectors remained in the PCB in case some assembly requires them or there is a lack of digital sensors. A memory module for an SD card completes the prototype, which was assembled inside an IP65 mechanised box (7.47 €) large enough to adapt to future

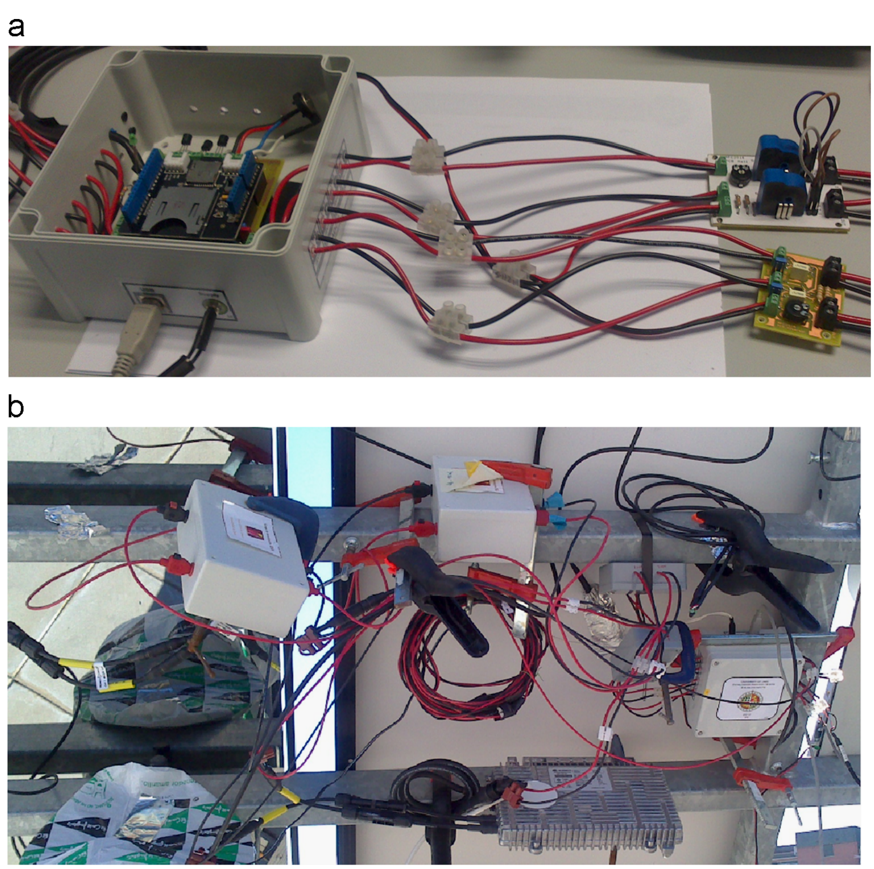

Fig. 5. (a) Final prototype assembly. Both purchased and constructed modules are stacked to enable easier and save number of interconnections, save space and increase the expansion capabilities of the prototype. The small PCBs on the right were required for high voltage and high current sensing. (b) The same prototype monitoring a PV grid-connected system. The data logger uses a module of two high common-mode voltage difference amplifiers to measure the current from the PV modules by means of shunts and an AC current transducer to measure the current from the micro-inverter.

specifications, e.g., module communication (GPRS or Bluetooth) or new stacked ADC module boards.

Some adaptor boards should be added to measure high voltage current sensing. This situation is typical in the monitoring of PV systems, for example, the current from the PV modules, grid, or batteries. In these cases, due to the low common-mode voltage of the ADC inputs, it is necessary to use high common-mode voltage difference amplifiers or current transducer (Hall-effect). In both cases, cost, power supply, and accuracy were studied to satisfy the prototype requirements and the IEC61724 standard. The amplifiers can manage the high common-mode voltage from the sides of the shunts, while the current transducers save these sensors. After managing several options, AD8479 and INA117 difference amplifiers and LEM® LTS15-NP and LTS25-NP Hall-effect sensors were chosen to accommodate the previously described premises. Some photographs of the last design are shown when the system was in the laboratory (Fig. 5a) and when it was used to monitor a small PV grid-connected system (Fig. 5b).

3.5. Prototype initial characterisation

Because one of the main objectives of this work is to design a data logger that meets IEC standards related to PV systems, the data logger characterisation was conducted to comply with such standards. The initial characterisation included verification of the linear response, verification of the stability response and verification of the temperature measurements and irradiance measurements, using low-cost shunts because they are the most restrictive. All of these studies are included in the electronic Supplementary Material of this manuscript, together with the prototype development process. The results indicate that the data logger is sufficiently accurate to comply with the IEC standards while using low-cost sensors.

4. Irradiance measurements

The accuracy of the irradiance sensor, including signal conditioning, must be better than 5% of the reading according to the international standard previously mentioned. Because the voltage measurements with the ADC used in the designed prototype are of sufficient accuracy for measuring sensors with a voltage output of microvolts, if the irradiance sensors have accuracies under 5% [35], the data logger reading will follow the IEC61724 standard.

The first phase of the irradiance measurements was performed to verify the previous assertion. This phase consisted of a comparison with the meteorological station at the University of Jaén, measuring calibrated pyranometers (CMP21 Kipp and Zonen™ in different positions) and one pyrheliometer (CHP1 Kipp and Zonen™ in a tracker) with constants of a few microvolts during both sunny and cloudy days to obtain the uncertainty, assuming that the sensors from the station were tracking the same weather patterns. This meteorological station uses an Agilent 34970 A data acquisition system of 22-bit resolution and a voltage accuracy of 0.004%. The results are shown in Fig. 6 and Table 2. The statistical parameters of the root mean square error (RMSE), which provides information on the variation of the measured values from the values of the reference multimeter, and the mean bias error (MBE), which provides information on the variation of the measured values from the reference ones, characterise the fitting of the comparison.

The second phase verifies the accuracy using inexpensive irradiance sensors based on solar cells, which have been widely used in photovoltaic systems to monitor the performance of PV plants. These solar cells are called 'reference cells', and their characteristics and calibration are defined in the international standards IEC60904-2 [20] and IEC60904-6 [21]. There are many studies providing performance comparisons between reference cells and pyranometers that support this use [36–39].

In the quest for inexpensive and reliable irradiance sensors, encapsulated mono-crystalline silicon solar cells were used, specifically ClickCells™ [40], and shunt resistors were connected to

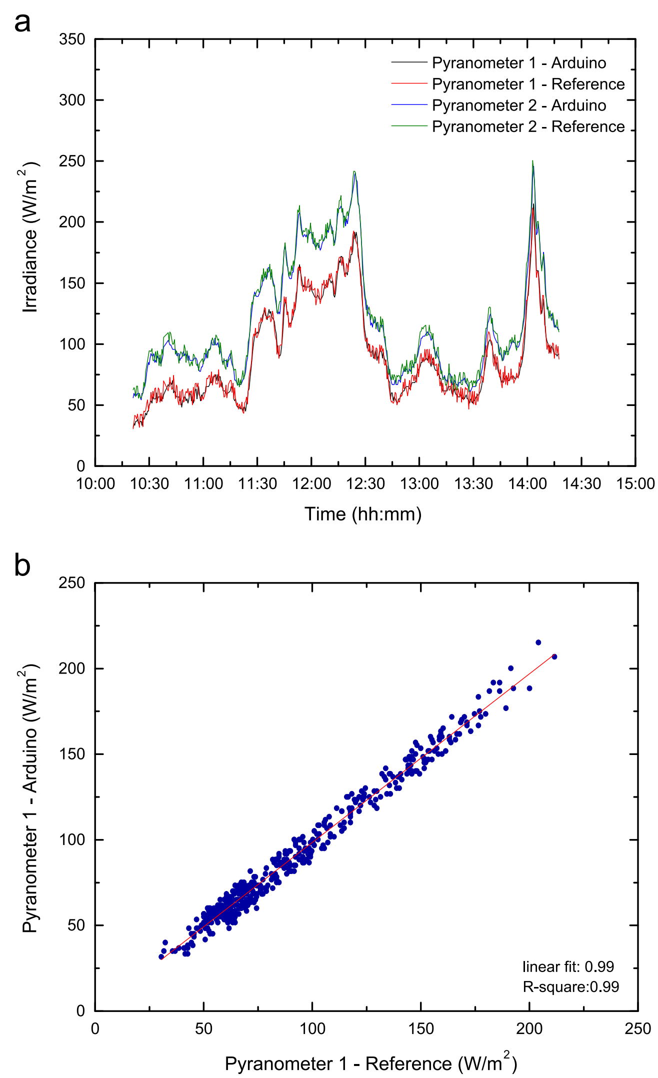

Fig. 6. (a) Detail of the comparison between the design and the pattern data logger (reference) in the worst conditions: cloudy and windy day with a gap of some seconds between the time-base. The *X*-axis shows the number of measurements in 30-second intervals. (b) Detail of the fitting for the data of pyranometer 1 (CMP21, Kipp and Zonen™) measured using the low-cost and the laboratory data logger.

Table 2
Results of the comparison between the design and reference data loggers in the worst (cloudy) and the best conditions. In spite of the gap of some seconds, which has less influence during sunny days, the combined uncertainty was below the 5% required by the standard. Both the RMSE and MBE are expressed in %.

Cloudy and windy					
Pyranometer 1		**Pyranometer 2**		**Pyranometer 3**	
RMSE (%)	MBE (%)	RMSE (%)	MBE (%)	RMSE (%)	MBE (%)
3.461457	−1.137859	2.713959	−1.443131	2.633756	0.637975
Sunny					
Pyranometer 1		**Pyranometer 2**		**Pyranometer 3**	
RMSE (%)	MBE (%)	RMSE (%)	MBE (%)	RMSE (%)	MBE (%)
1.160416	−0.455144	0.904653	−0.0524775	0.940627	0.260398

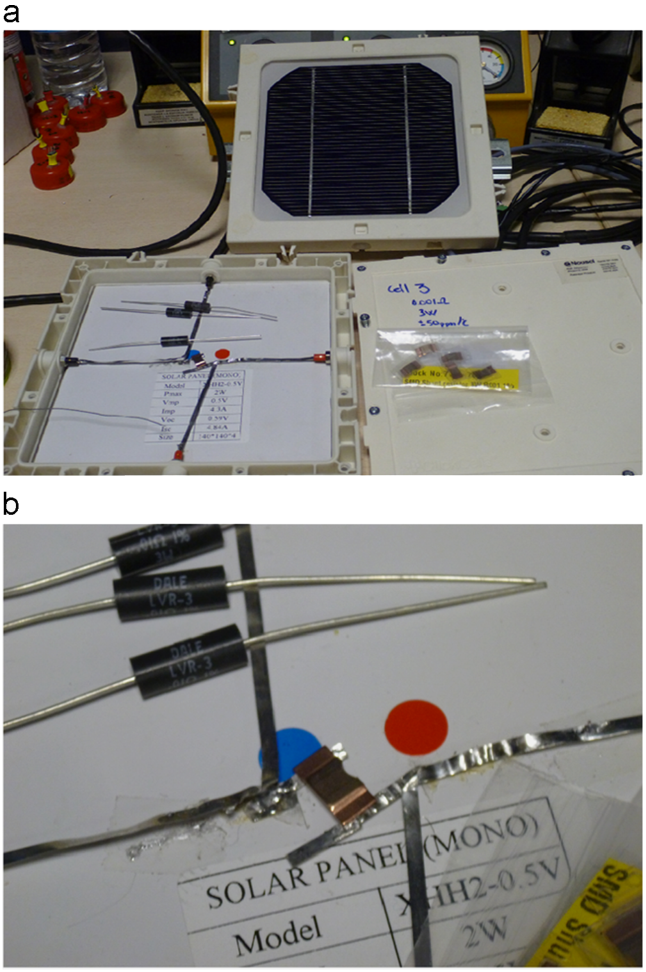

Fig. 7. Detail of the encapsulated photovoltaic cell from Nousol™. (a) Disassembling the back of the PV cell to weld the chosen shunt. (b) Preparation of the back ribbons to weld the low-cost shunt. It is very important to avoid the use of accessory wires or external elements to obtain a true response.

the cells for measuring I_{SC}. From eq. 1 and based on the advice of laboratories such as Ohm-Labs© or authors such as Braudaway [41], shunts below 2/3 of the rated current or power are used to avoid changing the resistance with temperature and losing linearity. Shunts of several values, low ppm/°C, 3 W and low-cost [42,43] were acquired for reference cells, whose power was approximately 2 W. Fig. 7 shows the process of assembling the shunt to the back of the reference cell.

The linearity of the shunts was tested in the laboratory, and they were fixed to the reference cells. The accuracy of the shunts was 1%, and the price was approximately 1€. For example, in a reference cell with I_{SC}=2 A at 1000 W/m^2, a 0.01 Ω shunt and 3 W power achieve the two conditions previously mentioned. The ADC will measure 20 mV at 1000 W/m^2. Because its sensitivity is 2 μV, the ADC can appreciate the changes, and the expanded uncertainty is 1.2%. As a result, to achieve the IEC standard of a level of accuracy below 5%, the uncertainty of the irradiance sensor chosen should be below 3.8%. The reference sensors were calibrated and compared with a pattern pyranometer (CMP21, Kipp and Zonen™), as shown in Fig. 8.

5. Four-month testing period under harsh environmental Conditions

Two reference cells initially used for the new data logger characterisation were set-up to be continuously monitored by

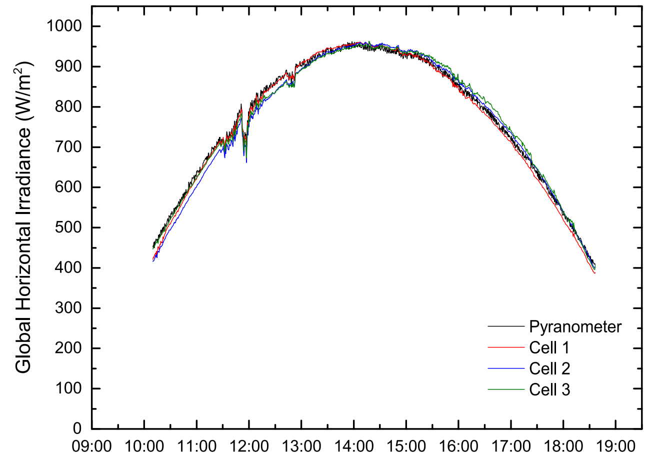

Fig. 8. Global horizontal irradiance measured by the pattern pyranometer (CMP21 Kipp and Zonen™) and the global horizontal irradiance measured by three reference cells [41] during a sunny day. A good level of fitting can be achieved despite the spectral mismatch.

the data logger for a period of four months, from July 2013 to October 2013, in the test facilities at the University of Jaén (Spain). This period corresponds to the summer months, and it usually contains some of the harshest environmental conditions for PV systems and data monitoring equipment, including temperatures up to 45 °C, dust storms (from winds from the Sahara Desert), electrical storms with high wind speeds and heavy rain that in some cases can lead to power shortages. The objective was to study the performance of the new data logger under extreme conditions and for a continuous period of time. At the same time, other reference cells were calibrated over a longer period of time.

5.1. Set-up

Two reference PV cells were connected to shunt resistors to monitor their short-circuit current continuously. A pyranometer (CMP21, Kipp and Zonen™) and a UV radiometer (FZAB/A/B, Huatron™) were also monitored by the data logger. The temperatures for conditions under the sun, under the shade, and inside the data logger case completed the monitoring set due to the low-cost temperature sensors (LM35). Fig. 9(b) shows the set-up for the calibration of the cells and testing of the data logger, with the data logger placed under the cells for direct solar exposure protection. Data from the meteorological weather station located in the same place (University of Jaén, Spain, latitude 38°N, longitude 3°W) were also available, providing data on the wind speed and wind direction, the ambient temperature, the humidity, as well as the global and direct irradiance.

5.2. General results

The results from the four-month testing period indicate how the new Arduino data logger monitored and recorded the data correctly for the complete period of time of 123 days (100% monitoring) in comparison with the commercial system that monitors both the weather station and the PV installation at the test facilities in the University of Jaén, which was either out of service or experiencing problems with the data acquisition for 10 days (91.8% monitoring) during the 4-month period. Problems with the commercial system occurred due to power shortages by storms that forced the technicians to initialise the software and perform maintenance. The Arduino data logger did not undergo changes in the data because it is designed to start-up without external help after power shortages (or can operate connected to a battery).

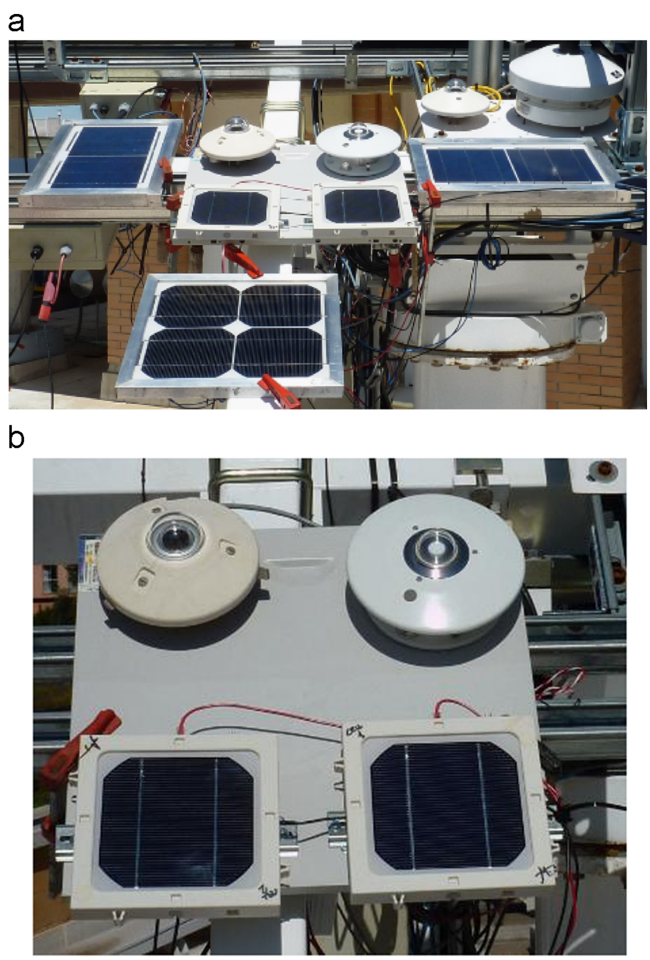

Fig. 9. (a) Detail of the assembly of the data logger to measure several reference cells. (b) Detail of the setup on the tracker for the four-month period. From left to right, top to bottom: Pyranometer CMP21, UV-sensor FZAB/A/B and PV cells in the calibration process using inexpensive shunt sensors.

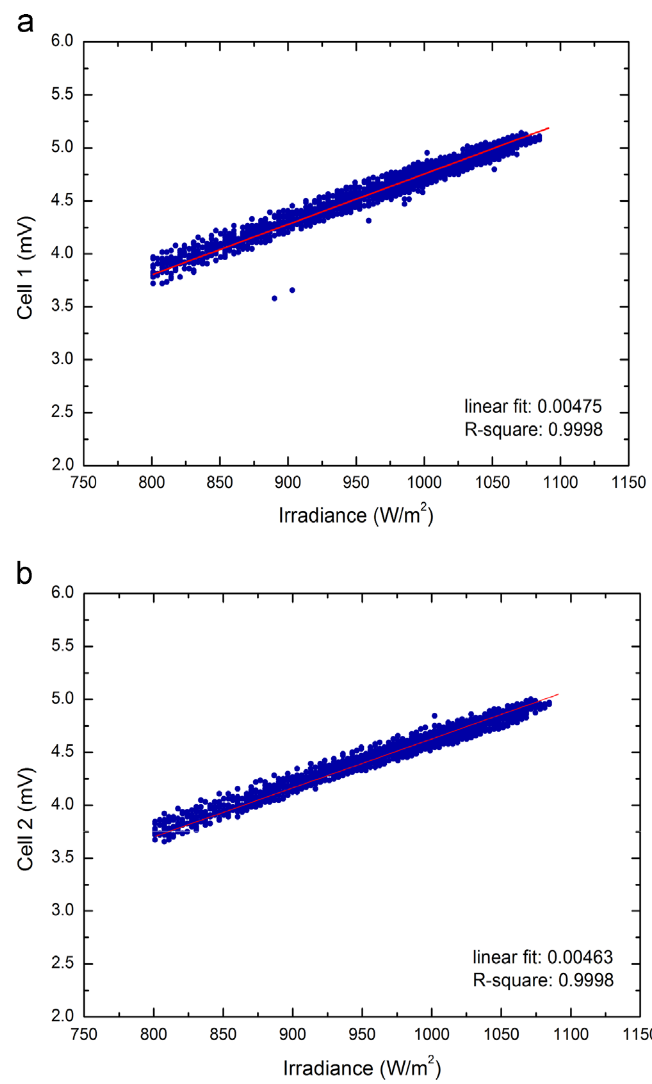

Fig. 10. Detail of the fitting for cell 1 (a) and cell 2 (b) versus the pyranometer (CMP21 Kipp and Zonen™) measured with the low-cost data logger during 4 months for irradiance values above 800 W/m^2.

The data monitored by the Arduino data logger, corresponding to the calibration of the two reference cells (Nousol™), are shown in Fig. 10, where the calibration of the cells was plotted for the total testing period. The data used were filtered, rejecting irradiances below 800 W/m^2, to minimise the sources of uncertainty.

The fitting of cell 1 is worse due to some problems with connectors after a summer storm. These problems were solved by carefully reviewing the cell 1 connection with the data logger. Unlike cell 1, cell 2 connectors did not experience any problem and the monitoring was correct. If calibration only includes clear days, for example, complete sunny days without clouds, the fitting does not vary.

5.3. Specific cases: 45 °C ambient temperature, heavy rain storm

Two specific cases of days with extreme climatic conditions are described in detail to reveal the good data logger performance even under harsh environments, both at the University of Jaén, Spain.

5.3.1. 45 °C indoor temperature (19.08.13)

Fig. 11 displays the daily profile of the irradiance and the temperatures (from the meteorological station and the low-cost data logger), wind speed, and the calibration results. The data taken by the data logger reveal the good fitting of the irradiance with the results of the meteorological station. The indoor temperature of the data logger increases during the day in relation to the ambient temperature and exceeds 45 °C with proper operation of the data logger, not only on this day but all of the days with summer temperatures.

5.3.2. Heavy rain storm and wind (07.08.13)

Fig. 12 displays the daily profile of the irradiance and the temperatures (from the meteorological station and the low-cost data logger), wind speed and relative humidity. The data collected by the data logger exhibit a good fit regarding the irradiance with the meteorological station, in spite of the gap between the time-base and the strong wind. The indoor temperature of the data logger increases during the day relative to the ambient temperature when the sun shines. The data logger operated correctly without errors during the three days of stormy weather.

In summary, during these four months, the data logger designed was found to be reliable, able to monitor all of the requested parameters with high accuracy, and able to withstand high temperatures and other harsh climatic conditions. Further testing, including several module technologies and test sites in different climatic regions, is planned for the next year to gain more knowledge on the performance of the proposed data logger in the long term regarding reliability and durability.

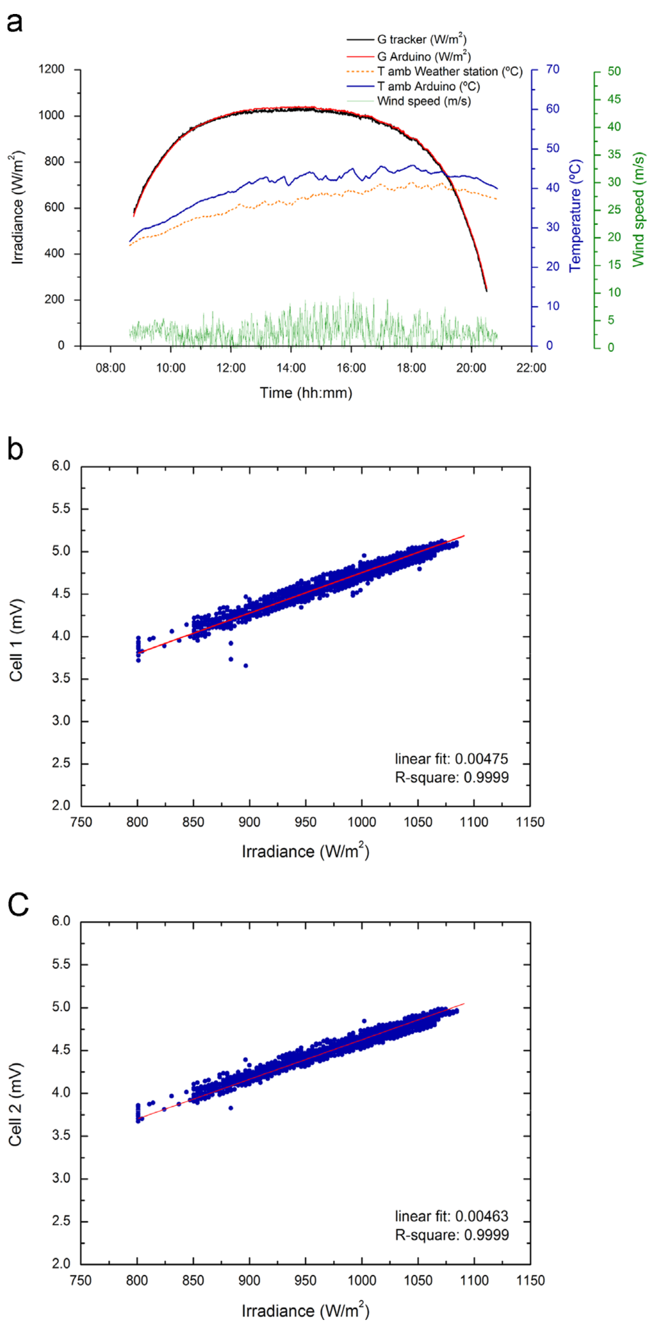

Fig. 11. Data from the Arduino data logger during a sunny and hot day (19/08/2013). (a) Comparison of the irradiance and the temperatures between the weather station and the data logger. (b) and (c) Calibration of the photovoltaic cells from Nousol™.

6. Testing photovoltaic systems

After demonstrating the behaviour and good accuracy of the low-cost data logger and sensors under harsh environmental conditions, the next aim is to monitor the main parameters in several PV systems, as emphasised in the IEC617247 standard. Two configurations were tested, a stand-alone PV system monitoring in real time [44] and a micro-grid-connected PV system, both located at the University of Jaén.

6.1. Stand-alone photovoltaic system

A one-week-long experimental campaign at the University of Jaén was performed to verify the performance of the Arduino data logger under IEC61724, which was part of the collaboration with the IDEA research group that allowed the connection of our system to their installations. There are three SAPV systems located at the University of Jaén [44]. Each system has a PV array of two PV modules in parallel (I-106) and a 12-V battery (200 Ah-C100VRLA), and the differences are in the type of charge regulator: two of the PWM (pulse width modulation) type and one of the MPPT (maximum power point tracker) type. The monitoring system is based on a graphical user interface that allows users to interact and check the operating status of the SAPV installations. The system is developed in LabView™ and uses an Agilent™ data logger of 22 bits (34,971 A). The parameters measured and recorded by this monitoring system include the PV generator output voltage ($V_{A,MOD}$), charge regulator output voltage ($V_{A,REG}$), battery voltage (V_S), load voltage (V_L), PV generator out current (I_A), battery current (I_S), load current (I_L), module temperature (T_{MOD}) and total irradiance in the plane of the array (G_I). There are 9 parameters: 4 voltages, 3 currents, 1 temperature and 1 irradiance.

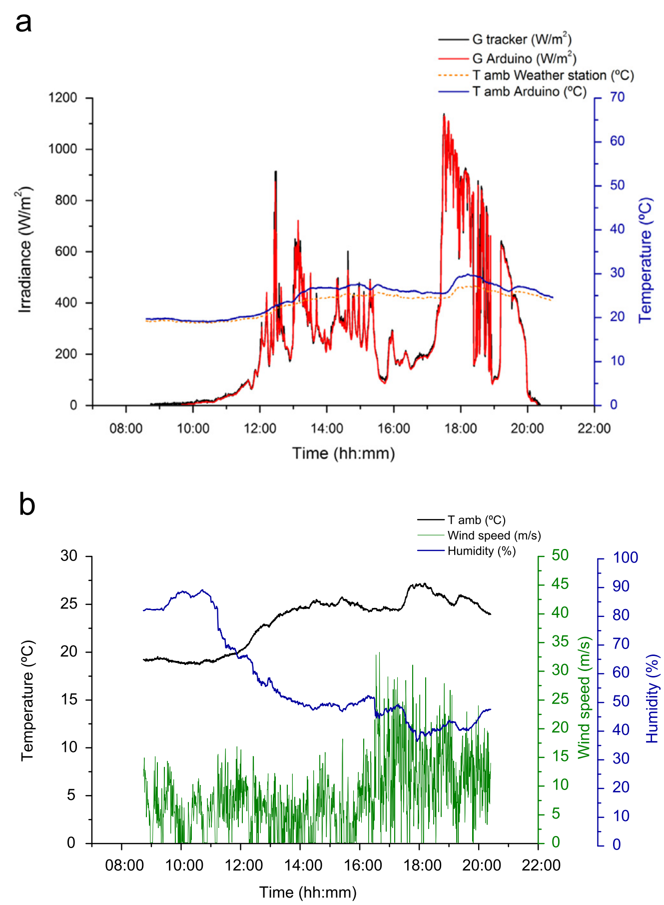

Fig. 12. Data from the data logger during a rainy day (07/09/2013) at the University of Jaén, Spain. (a) Comparison between the irradiance and the temperatures from the weather station and the Arduino data logger. (b) High wind speed and humidity figures during the windy and rainy day.

The system used has a charge regulator with MPPT, and the low-cost data logger monitored the following parameters for one week in January 2014: $V_{A,MOD}$, $V_{A,REG}$, V_S, I_A, I_S, I_L, T_{BAT}, T_{amb} and G_I. Six digital temperature sensors were used to measure only T_{BAT} and T_{amb} to test the repeatability of the measurements, and the result indicated variations smaller than ± 0.2 °C. Three voltage dividers of 1/48.4 V were implemented in the PCB (resistors of 474 kΩ and 10 kΩ). Two common-mode voltage precision difference amplifiers (AD8479) were added to one of the ADCs to avoid damage to their analogue inputs when high voltage current

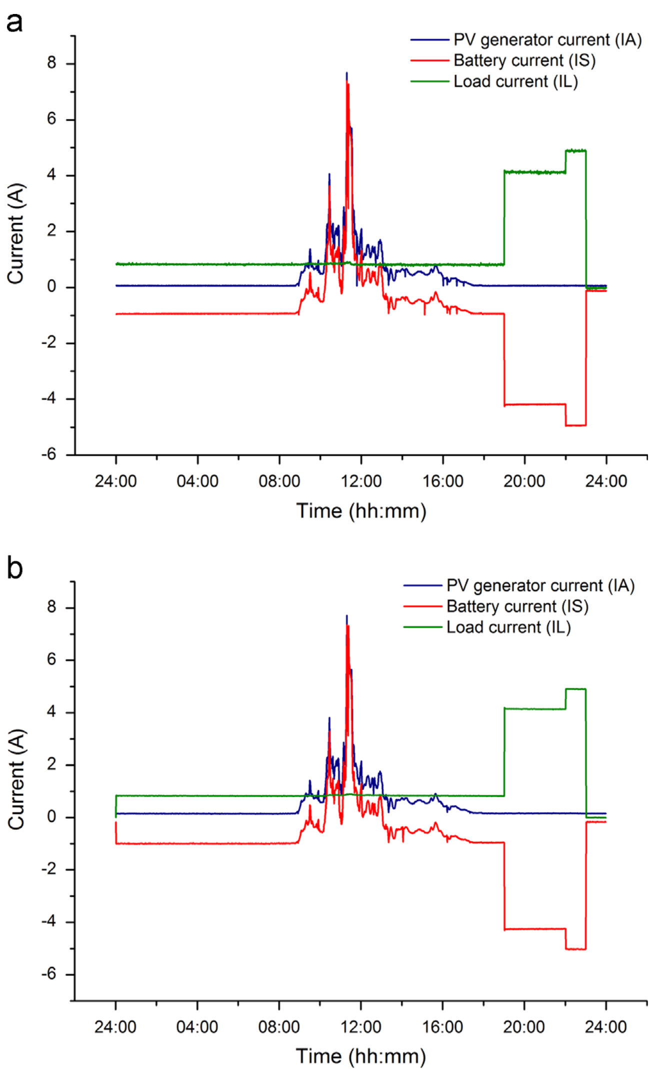

Fig. 13. Comparison between the currents measured by the Arduino data logger (a) and the monitoring system located at the University of Jaén (b) on 15/01/2014. The low-cost data logger collects the data every 30 s, while the monitoring system [44] collects the data every minute; as a result, more peaks were observed by the Arduino data logger during the hours of solar irradiance.

sensing was used in PV systems (see Fig. 5a) to measure I_A and I_S. We used the same shunts as those of the SAPV system, connecting our cables in parallel to avoid changes in the original monitoring system. A Hall-effect sensor to measure the currents (I_L, I_S) with the ADC directly was also used, specifically LTS-15NP from LEM™, with high accuracy and low cost. The results are shown in Figs. 13, 14 and 15. The comparison between both monitoring systems is quite good, taking into account that the low-cost data logger based on Arduino collects the data every 30 s instead of every 60 s for the monitoring system at the University of Jaén, thus obtaining more data and peaks in the signals.

Both the common-mode voltage precision difference amplifiers and the Hall-effect sensors were calibrated previously to match the uncertainty of the IEC61724 standard. Two small boxes were built to contain the two precision difference amplifiers and two Hall-effect sensors to compare their behaviour. The amplifiers are less expensive than the Hall-effect sensors, but if high currents must be measured, the shunts increase the cost of the amplifiers, making the Hall-effect sensors the best option to maintain the accuracy. This need to use Hall-effect sensors is common to all data loggers, low and high cost, because most of them are designed to measure voltage, not current, and they must convert this current to a voltage magnitude.

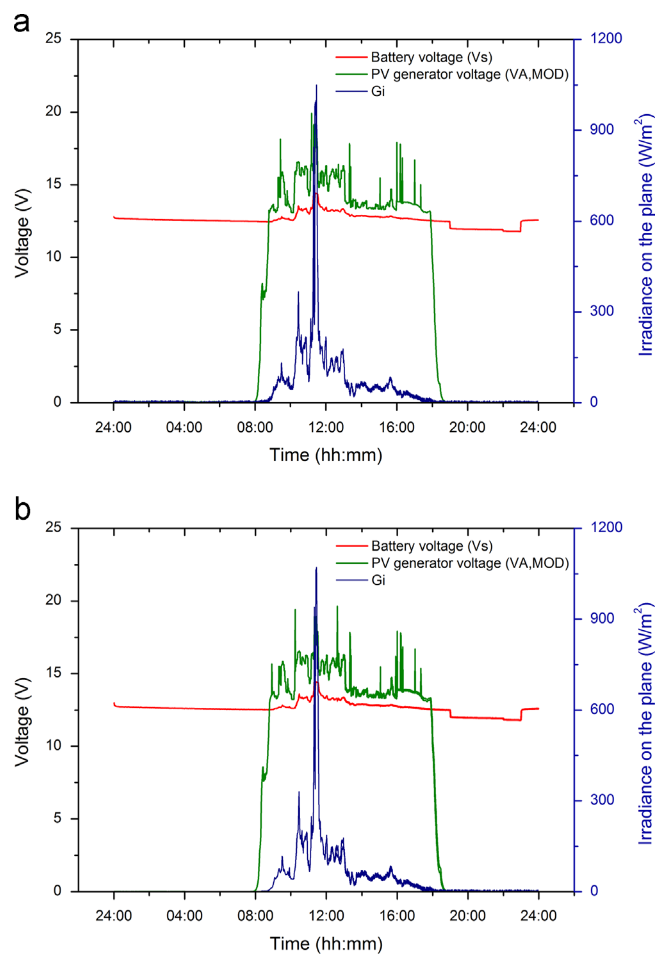

Fig. 14. Comparison between the voltages and irradiance collected by the Arduino data logger (a) and the monitoring system located at the University of Jaén (b) on 15/01/2014. This day was a cloudy day.

6.2. Micro-grid-connected photovoltaic system

The other typical configuration of a photovoltaic system is the grid-connected system. Although the idea is to develop a large experimental campaign in a PV installation to test the convenience of this low-cost design, a micro-grid PV system was built at the University of Jaén to perform a similar test. The system consists of two CIS PV modules with similar electrical characteristics (Shell PowerMax® Eclipse 80-C and Würth Solar® GeneCIS75) and one micro-inverter ENECSYS® SMI-240. The details of the system are shown in Figs. 5b and 16.

The components used were those available in the lab, although the micro-inverter will function better with more power in its input. In our case, the efficiency was not the goal, but this set up was suitable to check that the low-cost data logger can monitor a small grid-connected PV system using the appropriate sensors. The global irradiance in plane was measured using a pyranometer (CMP21 Kipp and Zonen™) and a calibrated PV cell (Nousol™), the wind speed was measured using a Young™ anemometer (12102), and the ambient temperature together with five temperatures distributed on the back of the two PV modules were measured using the digital temperature sensor DS18B20 (low-cost). The PV generator voltage was measured using the voltage divider 1/48.4 described previously. Both PV module currents were measured using the module with the two precision difference amplifiers, taking advantage of the use of the available shunts in the lab of 4 A–60 mV. An AC current transducer acquired for this assembly was used to measure the AC output current from the micro-

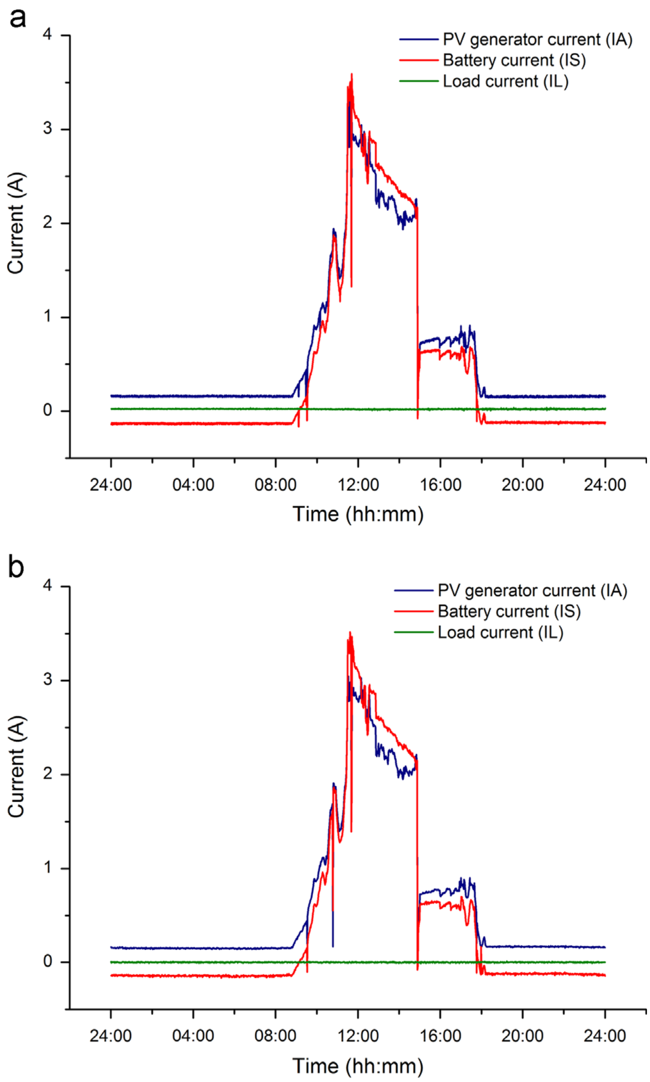

Fig. 15. Comparison between the voltages together with the irradiance using a different charger configuration of the Arduino data logger (a) and the monitoring system located at the University of Jaén (b) on 21/01/2014. The day was a partly sunny day.

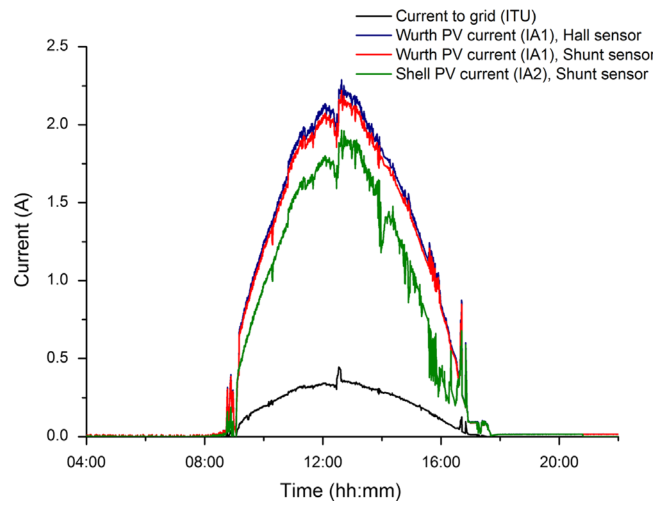

Fig. 17. Detail of the currents measured by the Arduino data logger on 25/01/2014. The different fill factor of each PV module, connected in parallel, makes the micro-inverter MPP algorithm unable to determine the most efficient point. As a result, the maximum currents are different for each PV module.

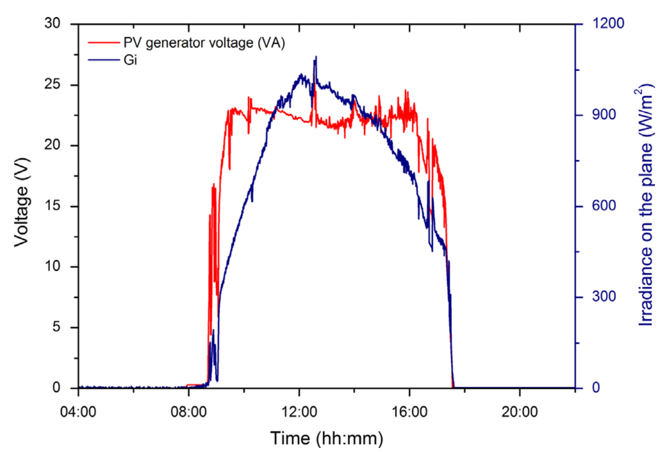

Fig. 18. Detail of the global irradiance in plane (CMP21 Kipp and Zonen™) and the PV generator voltage (by means of the voltage divider) measured by the Arduino data logger. The micro-inverter fixes the voltage via its MPP algorithm.

Fig. 16. Detail of the micro-grid system design at the University of Jaén, Spain. The PV generator is composed of two CIS PV modules in parallel and one ENECSYS inverter. The low-cost data logger measured the irradiance in the plane from two sensors (a pyranometer and a calibrated cell), the wind speed, PV generator voltage, PV currents from the first and second modules, the output current from the inverter via an AC Hall-effect sensor AT-B5 self-powered and six digital temperatures, ambient temperature at the shade and five temperatures distributed on the back of the two PV modules, using digital temperature sensors.

inverter. The chosen transducer was the AT-B5 from LEM®, self-powered with a DC output and small uncertainty. Although some problems occurred at the beginning with the start-up of the micro-inverter and most of the days were cloudy, we collected enough data to check the suitability of the low-cost data logger to monitor a small grid-connected system or larger ones with the adaptation of the sensors. The currents from the two PV modules (the Würth PV module current measured both with a Hall-effect sensor and a shunt) and the current to the utility grid from the micro-inverter are shown in Fig. 17. The efficiency of the system is low because the PV modules have different electrical parameters, although they are very similar (V_M and I_M), and the MPP algorithm was functioning far from the maximum power point (Fig. 18). The analysis of the six temperatures indicated that they are very similar when the sunset arrives but that the temperature of the PV modules is lower than ambient temperature at night. Both PV modules exhibit lower temperatures in their middles than in their edges or near their box connection (from 0.2 °C – Shell – to 0.7 °C – Würth – on average), but the Shell PV module exhibited higher temperatures than that of the Würth PV module (0.6 °C on average), despite being located in the outer part of the structure (see Fig. 19).

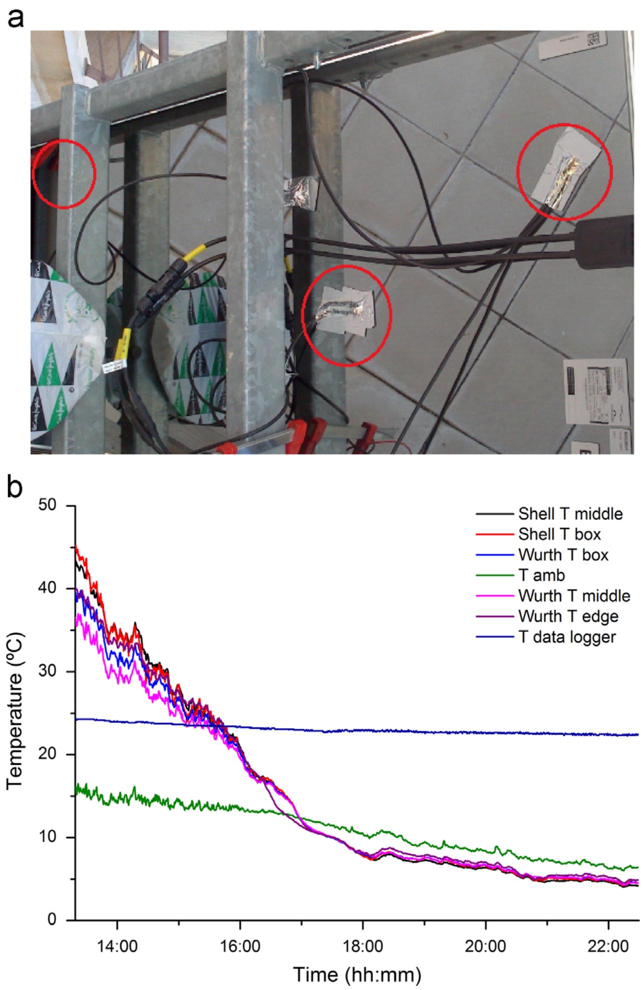

Fig. 19. Temperatures determined on the backside of the PV modules, together with the ambient temperature in the shade and the operating temperature of the data logger. (a) Detail of the situation of the three digital temperature sensors fixed with aluminium tape on the Würth PV module (red circles). (b) Behaviour of the temperatures depending on the position of the sensors on the backside of the PV modules.

7. Consumption and budget summary

The objective of this work was to build a low-cost data logger that is portable, autonomous and accurate. The budget for the data logger is described in Table 3. The final cost of the last prototype, with 8 analogue inputs of 18 bits (five of them with voltage dividers capable of measuring up to 96 V), 3 analogue inputs for low-cost temperature sensors and unlimited digital temperature sensors, was approximately 63 €, which could be reduced considerably when mass produced and introduced into the market. Moreover, if it was necessary to perform high-voltage current sensing, some modifications using difference amplifiers and Hall-effect current sensors were tested, increasing the cost by approximately 30–50 €, taking into account that most of the usual data loggers in the market will also require similar modifications.

The data logger current consumption was approximately 50 mA in the worst case (when data are recorded), without using all of the possibilities that the software offers to reduce it. Several tests were conducted, using a sleep interval for the system between measuring intervals and the narcoleptic library provided by the Arduino users. The consumption was reduced by approximately 40%; however, sometimes, the data lines were not recorded in the memory, which requires an in-depth study. In the final prototype, the software features for reducing the amount of consumed power were not

Table 3
Budget for the low-cost portable data logger. Low-cost sensors were taken into account in the design and the final price. (www.satkit.com; www.aliexpress.com; www.farnell.com; www.rs.com).

Boards	Components	Price (€)
Arduino UNO Board	Stocked Board	15.6
ADC Board	2 MCP3424 SOIC	7.10
	DS1307 SOIC	2.72
	DS1307 parts: Battery, Cristal, Resistors	3
	Precision Resistors, Capacitors	7
	Stocked Board, Connectors	9
Memory Board	Stocked Board	6.65
	Memory 2 GB	2
Box	IP65 Container	7.47
	Wires	0.50
	Connectors	1.8
Specific adaptors for high voltage current sensing (*optional*)	1 AD8479 Soic	5.27
	1 INA117 Soic	6.60
	1 LTS-15NP LEM	15.43
Sensors low-cost (*optional*)	4 Shunts	4.8
	3 Analogue temperature sensor LM35	6
	6 Digital temperature sensor DS18B20	7.2
	1 Irradiance sensor (*monocrystalline cell with shunt,* www.nousol.com)	35.9
	Total without sensors	62.84
	With specific adaptor: AD8479 + shunt + PCB (3 units)	28.41
	With specific adaptor: INA117 + shunt + PCB (3 units)	32.4
	With specific adaptor: LTS-15NP + PCB (3 units)	55.29

implemented because data acquisition was considered more important than power consumption, although a power range of 0.7 W–0.35 W (14*V* – *V*50 mA) is sufficiently small to be supplied with some PV cells or by a small stand-alone system (battery – PV-cells – regulator) whose regulator could be implemented by the same Arduino processor. This stand-alone system is being developed now.

8. Conclusions and future guidelines

A new low-cost portable data logger meeting the accuracy requirements established by the IEC61724 standard related to photovoltaic monitoring systems was presented. The system design features easy-to-obtain hardware and free software, making it accessible to any researcher or user for the development of systems of their own design and use. This flexibility makes the system more suitable for each intended application, such as the monitoring of PV plants and the collection of data at remote locations in developing countries. The cost of the proposed system is considerably lower than commercially available devices, with little loss of accuracy and precision. The new low-cost data logger developed in this study achieves a cost of approximately 60 €, with 8 analogue inputs of 18 bits with a wide voltage range (currently up to 96 V), 3 analogue inputs for low-cost temperature sensors and an unlimited number of digital temperature sensors. The least expensive data logger currently found on the market, with eight inputs but only 12-bit resolution and a voltage range typically below ± 30 V, costs approximately 180 € and requires interfacing to a computer.

Furthermore, a study on the use of low-cost sensors for monitoring PV systems was conducted. The digital temperature sensor DS18B20 allowed the achievement of accurate measurements with a low price and only a three-wire cable with a one-wire bus. The reference cells manufactured by encapsulating silicon PV cells and using inexpensive shunts (36 € in total) are another solution to measure irradiance at low-cost as an alternative to expensive pyranometers, although annual calibration is required to guarantee accuracy and performance. Stand-alone and grid-connected photovoltaic systems were monitored using some difference amplifiers, shunts, and Hall-effect sensors to adapt the measurement to the designed data logger. The comparison of the results with those of other monitoring systems was very positive, with an uncertainty that complies with the IEC61724 standard.

An outdoor campaign of over six months was performed using the data logger in several configurations, and the results of the campaign indicated that the data logger is reliable, monitoring all of the requested parameters with high accuracy, and is able to withstand high temperatures and other harsh climatic conditions, such as rain and wind. This data logger warrants further study of its use for both research and for applications in developing countries. The next steps are to achieve lower power consumption and to develop a small stand-alone PV system implemented with Arduino. In addition, the communication aspects using wireless technologies, such as Zig-bee® and GPRS modules, will be studied, analysing the cost thoroughly in this case because the cost can increase rapidly with the addition of features, thus limiting the number of low-cost applications.

Acknowledgement

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.solmat.2014.08.008.

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