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Monitoring system based on IEC standards for irradiance and module temperature measurements in photovoltaic systems

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Abstract. Monitoring photovoltaic (PV) systems is necessary to assure their proper functioning. Mostly automated data acquisition systems (DAQ) are used for this purpose. Obtained data from DAQ are important for analysing the energy behavior of PV systems with any anomalies that may appear. It helps investors to realize economic calculations which use to estimate the return on investment. The article aims to present an open-source system that allows the acquisition and reliable recording of meteorological parameters that influence in the energy production of PV installations. The measurement processes were tested by different methods in order to comply with the standards of the International Electrotechnical Commission (IEC).

1. Introduction and problematic framework

The main sources of the electrical generation in Peru are hydroelectric and thermoelectric plants based on natural gas. The production of electricity in Peru in 2008 to 2015 using fossil fuels reached 20.8 TWh, while 22.3 TWh were produced by hydroelectric plants which represents 50.4% of the total energy produced. Fossil fuels are an exhaustible future energy source that has environmental effects on climate change and pollution emitting up to 200.6 MtCO₂-e in 2015 [1]. Therefore, the Peruvian Government is considering renewable sources for energy production and new distribution forms that can work with the existing power lines. Several solar parks have been constructed through international governmental tenders. Furthermore, the government published the Decreto Legislativo N° 1221 allowing for a grid connection of small systems (distributed energy). However, the required regulations for its implementation is still missing. Other provisions for the use of renewable energy, for example regulations for small rural systems (law No. 28749) exist.

Photovoltaic technology, which has had the highest growth rate in the last decade worldwide level, is based on the photovoltaic (PV) effect that allows the direct conversion of solar radiation into electrical energy. PV energy production in the rural sector is carried out utilizing isolated PV systems using batteries. The most successful application is the grid-connected photovoltaic PV System that allows a high degree of modularity in terms of power and the direct injection of electrical energy into the commercial distribution network [2].



Around the world, grid-connected photovoltaic PV Systems are very successful and receive the most attention due to their use in residential areas with electricity. As a result, it helps to decentralize energy production and reduce the costs of distribution. Compared to isolated (island) systems, they are very successful because they can constantly supply electricity to the grid and be used for auto-consumption. Costs are lower because a battery is not necessary; they are highly simplified and are subsidized or counted on other incentives in many countries [3].

In order to evaluate the PV potential of a geographical area, in addition to satellite data, experimental installations around the country with data acquisition system (DAQ) are essential to evaluate the viability of a possible PV energy generation. Verification of the possible energy production and identifying possible anomalies are helpful to improve proper functioning.

Unfortunately, monitoring systems for PV applications are costly. Furthermore, specific sensors frequently demand proprietary software that works only with this system [4]. Therefore, interconnectivity frequently is complicated; the accuracy is not always guaranteed. Often, commercial systems do not have sufficient sensor inputs, and modifications are difficult.

The main objective of this work is to detail the design of a monitoring system that acquires irradiance and temperature and complies with the standards of the International Electrotechnical Commission (IEC); the reference standard is IEC61724-1 [5]. Also, it must be adaptable for different PV applications; it must use open-source hardware and software to monitor the behavior of the grid-connected PV system; power consumption should be low.

2. Acquisition of irradiance and module temperature in PV systems

To measure the meteorological parameters with the most significant influence on the operation of grid-connected PV systems or another application with PV technologies, it is necessary to comply with the requirements specified in the IEC61724-1 [5]. For meteorological parameters, it is required to collect data of irradiance and PV module temperature.

In PV modules, the irradiance influence in their maximum power (P_{max}) and the short-circuit current (I_{sc}), as shown in equation (1) [6]. This equation also shows the relation between the measured current and nominal current which is provided by the manufacturer in standard test conditions (STC), irradiance of 1000 W/m^2 , spectrum AM 1.5 and cell temperature of $25 \text{ }^\circ\text{C}$ [7]. The incident irradiance is measured by pyranometers or calibrated modules.

$$\frac{G_I}{1000 \text{ W/m}^2} = \frac{I_{sc,measured}}{I_{sc,STC}} \quad (1)$$

The electrical behavior of PV modules is also influenced by temperature. The increase of temperature in cells of PV modules causes a decrease in the open-circuit voltage (V_{oc}), which is the maximum voltage that the PV system provides when it is not connected to any load. If the temperature of the module (T_m) increases, the V_{oc} decreases. The module temperature is related to the irradiance because as it increases, the temperature of the module also rises [6].

On the other hand, the acquired parameters are used to estimate the performance of PV installations, it is evaluated by the final yield, reference yield and performance ratio [5]. The final yield is the relation between energy generated during a defined period (day, month, or year) and the nominal power installed. It represents the equivalent time that the PV system operates at its nominal installed power and can estimate the return on investment [8].

The reference yield is the relation between the irradiation in the place of interest and the irradiance at STC. It represents the equivalent time that the irradiance is at 1000 W/m^2 in this place. Therefore, the reference yield depends on the irradiation measurement (kWh/m^2), which can be obtained by the time integration of the irradiance in the PV surface (kW/m^2) during a defined period (day, month or year).

To evaluate the performance ratio (PR) of the grid-connected PV systems, the final and the reference yields are needed. The relation of these two gives the PR, which indicates whether the system is operating correctly and allows the analysis of losses effect [8].

References [9] to [11] indicate that the PR, final yield and reference yield can be determined with the parameters obtained through the proposed DAQ system. Furthermore, experimental data will allow the evaluation of the installations and operation of the system.

The minimum parameters that need to be acquired for an accurate evaluation of PV systems are presented in table 1, which is consistent with the parameters and accuracy requirements of IEC 61724-1 standard. The DAQ system must be adaptable to multiple sensors that allow the accurate recording of the irradiance and module temperature. In this case, they must be tested with reference sensors that verify their correct operation.

Table 1. Meteorological parameters to be measured in real-time as required by the standard IEC 61724-1.

General Parameters	Specific Parameters	Symbol	Accuracy
	Irradiance in the PV plane	G_T	RMSE < 5%
Meteorological	Temperature of PV module	T_m	± 2 °C

3. General Design of data acquisition system

DAQ system is composed of dedicated hardware and software, which allows information to be extracted from different measurement sources. In this regard, these systems have direct communication with a computer, which allows displaying the data obtained in a graphic interface [12]. The system to be designed registers and shows in the interface the parameters: global irradiance, irradiance in the PV surface (W/m^2) and module temperature ($^{\circ}C$), which directly influence the electrical behavior of photovoltaic (PV) technologies [6].

Figure 1 shows the DAQ system's connections with temperature sensors in 3 different module PV technologies and two types of irradiance sensors. This connection allows the recording of these parameters in the DAQ and they will be sent to the computer that will facilitate their recording and visualization in the graphic interface.

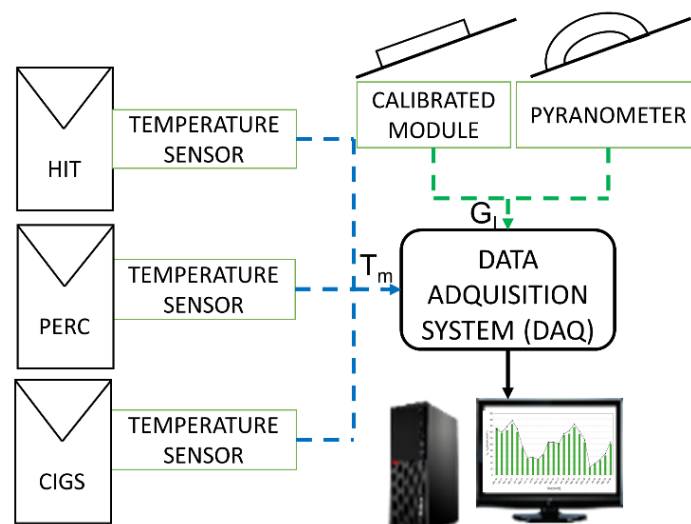


Figure 1. Irradiance and temperature sensors connected to DAQ system.

The block diagram presented in figure 2 shows the general connection scheme of different sensors used to acquire the parameters which affect the PV modules. The irradiance measurement (G_T) will be

acquired with two instruments, pyranometer and a calibrated PV module. The pyranometer is an instrument that measures the global irradiance in a range of 0 to 2000 W/m². The calibrated PV module is composed by a solar mini-module of 5 W that is short-circuited at its terminals using a resistor.

Both sensors for measuring irradiance in the plane of the array provides an analog output. Therefore, the data must be sent to the data recording unit (ATMEGA328P) using an analog-to-digital converter (ADC), which requires a resolution that complies with the standard IEC 61724-1. According to these requirements, it is needed to register at most steps 1 W/m², resulting in a resolution of 11 bits. To avoid missing bits of irradiance information and exceeding the maximum error allowed of 20 LSB. This resolution needs to be overestimated according to the component which will be used and the error specifications provided by the manufacturer.

A 16-bit resolution ADS1115 with a programmable gain amplifier is chosen, and this module has a maximum error of 10 LSB. Hence, there is no need to amplify the input signal from millivolts (mV) up to 5 V. This component will allow the connection to the DAQ system up to 4 inputs for irradiance sensors (analog pyranometers or calibrated modules). Each one must be calibrated with a reference sensor to obtain data that complies with the IEC standard.

To measure the PV module temperature (T_m), two RTD sensors are mounted to the panel's back-side, one at the center, another at the corner with their respective digital signal converter (MAX31865). RTD sensors vary their resistance when the temperature is attached to changes. The standard requires a measurement resolution below 0.1 °C. As a result, it is estimated that a minimum digital resolution of 11 bits is needed, but to avoid losing digital data and exceeding the maximum error allowed of 20 LSB, this resolution must be overestimated. Hence, a 15-bit ADC with a maximum 6 LSB error is used to convert the RTD signal to record the PV module temperature.

The MAX31865 module works with an RTD sensor by generating a current of 5.75 mA and measuring the voltage across it. Depending on the PT100 resistance at a certain temperature, a voltage signal will be sent to the respective ADC. Both converters send digital data to the recording unit for transfer to the computer through a module based on the RS-485 protocol.

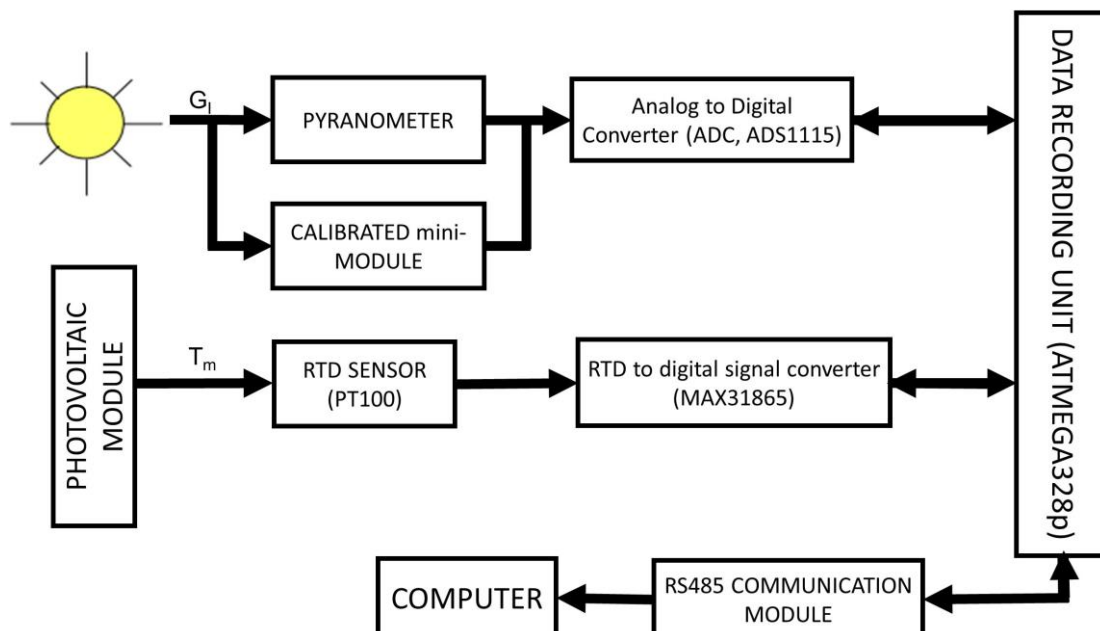


Figure 2. Block diagram of connections for irradiance and temperature sensors with their signal converters.

The IEC standard recommends a sampling period no greater than 1 minute for the recording of irradiance and module temperature. Therefore, it is necessary to know the operating time of the

components chosen. To adapt the irradiance signals, ADS1115 has a real-time conversion rate of 1,16 milliseconds, and this process keeps constant for acquiring the digital data to the ATMEGA328P.

The 15-bit ADC of the MAX31865 module for the temperature record, has a constant conversion time range of up to 66 milliseconds. This conversion is realized constantly and does not depend on what is being transmitted to the acquisition unit, so it does not influence the required sampling period.

To achieve a correct calibration, the measured sensors should be compared with referential instruments. To this end, the mean square error (RMSE) and the mean bias error (MBE) are calculated with the equations (2) and (3), respectively, identifying the relative error between measured data with the DAQ system ($M_{DAQ\ system_i}$) and values of the referential instrument for calibration ($M_{ref\ system_i}$). RMSE (%) can be used to calculate the dispersion level and the average error of the recorded data to evaluate the results. MBE (%) is used to estimate the model's average bias and to decide if it is necessary taken to correct the model bias. A positive bias or error in a variable represents the data from datasets is overestimated and vice versa [8].

$$RMSE(\%) = 100 \times \frac{\sqrt{\frac{1}{N} \sum_i^N (M_{ref\ system_i} - M_{DAQ\ system_i})^2}}{\frac{1}{N} \sum_{i=0}^N M_{DAQ\ system_i}} \quad (2)$$

$$MBE(\%) = 100 \times \frac{\frac{1}{N} \sum_i^N (M_{ref\ system_i} - M_{DAQ\ system_i})}{\frac{1}{N} \sum_{i=0}^N M_{DAQ\ system_i}} \quad (3)$$

DAQ system will be installed with the Grid-connected PV Systems outdoor. This system can connect up to 4 irradiance sensors sending each 16-bit digital data to the recording unit. Also, up to 7 RTD temperature sensors can be connected by sending each 15-bit digital data to the recording unit. For this reason, a maximum of 170 bits must be transmitted in total for each sampling period. Considering a minimum period of 100 ms, the transmission rate will be 1.7 kbps.

In this case, the maximum distance from a laboratory to the PV installation will be 75 meters. The serial communication of ATMEGA328P can reach a maximum speed of 2 Mbps until 15 meters away (correct transmission is not ensured with longer distances). Another possibility is the communication through the RS-485 protocol which is the most commonly used in the industrial sector.

The MAX485 module based on Modbus or RS-485 protocol [13] is chosen. It allows the data transmission with a maximum distance of 1200 meters. These affect the transmission speed; for distances lower than 12 meters, the typical transmission rate is 2.5 Mbps. On the other hand, for distances up to 1200 meters, it has a maximum speed of 100kbps, which complies with the needs described previously (distance = 75 meters and transmission speed = 1.7 kbps). In addition, the data transmission period from the ATMEGA328P to the MAX485 is 67.6 microseconds. As a result, it does not affect the data transmission period because this is a short time compared to the standard sampling period.

All the selected components are mounted on a printed circuit board (PCB), as shown in figure 3. This PCB allows the connection of the components to their power supply and to the ATMEGA328P. The DAQ system needs to be suitable for outdoor installation, so the PCB with all the components is to be mounted in a polyester board with a minimum protection level of IP65 as specified in IEC 60529 [14], where the components are isolated from dust particles and protected against water jets.

A thermomagnetic switch is installed on the board to control the system's ignition, realizes the protective function against short-circuit failures in the power lines. The switch allows the connection between the 220 V line and a 24 VDC power supply. The pyranometers and components of the DAQ system connected to the power supply consume up to 1.3 A. For this reason, the power supply chosen can provide a maximum current of 3.2 A.

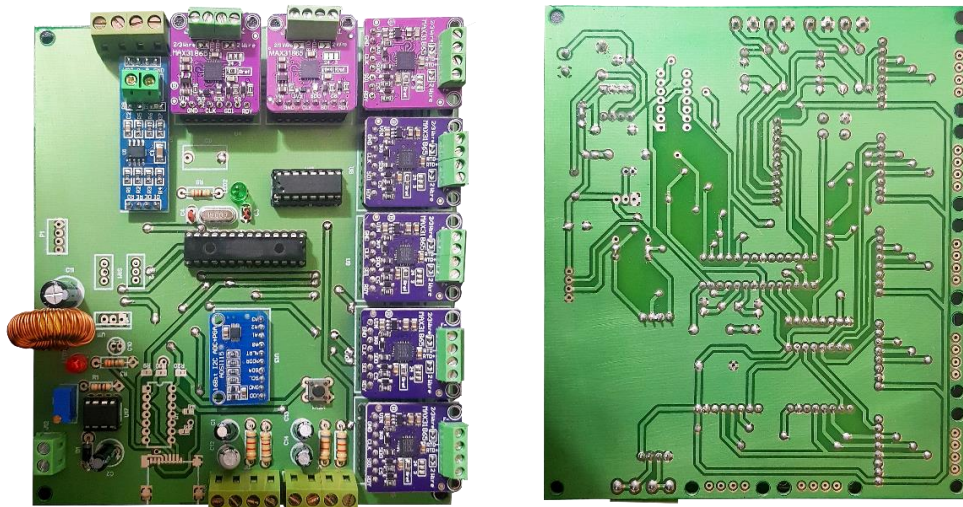


Figure 3. Electronic board of the DAQ system for the acquisition of irradiance and module temperature.

The monitoring system will be able to receive 24 V since it has a DC voltage regulator circuit, which will reduce the voltage level to 5V to supply the different components of the acquisition system. As a general diagram of the operation of the DAQ system, figure 4 shows the integrated modules being used to acquire and convert the signal from the sensors. The connections, operation, and data transmission of the general circuit for the DAQ system is specified in detail below.

The ADS1115 module converter uses the I2C protocol [15] to transmit the data to the ATMEGA328P. The connections are shown in figure 4, where 2 digital pins are needed for the clock signal (SCL) and for the module's serial data signal (SDA), which allows the communication of digital data between the module and the recording unit (ATMEGA328P).

The PV module temperature is acquired through the MAX31865 module, which communicates with the ATMEGA328P through the SPI protocol having up to 4 connections. Each module must be connected to the same serial clock line (SCK), serial data input (SDI), and serial data output (SDO), but the chip selector input (CS) must be connected separately to a digital pin of the chip.

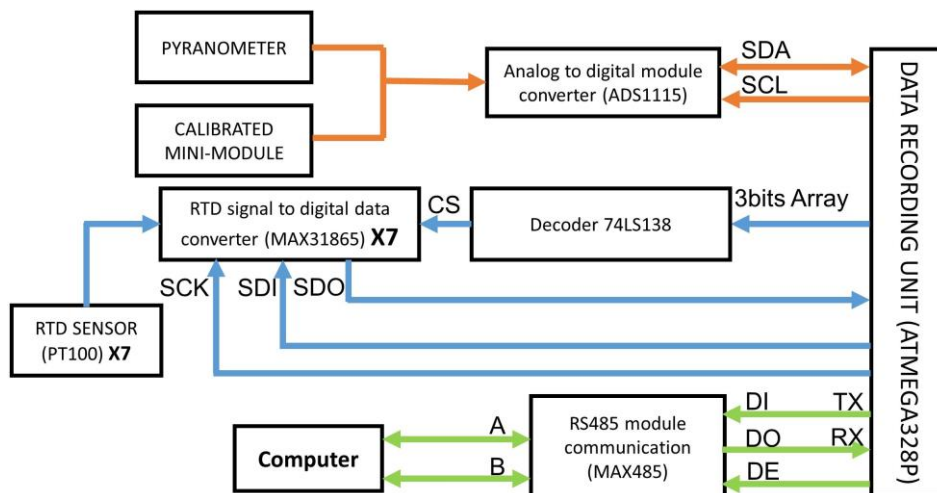


Figure 4. Operating diagram, connections and data transmission to the data recording unit and the computer.

The ATMEGA328P does not contain enough digital inputs for the 7 modules that need to be installed because it would require up to 7 digital pins for each CS connection, and in total, with the other inputs, should have 10 digital inputs out of 14 that this recording unit has. Therefore, as shown in figure 4, the board has a decoder with a code 74LS138, which requires 3 digital pins of the ATMEGA to generate a 3-bit array in order to enable each CS sequentially depending on this array with 8 possible cases to be used 7 of them.

The MAX485 uses the ATMEGA serial communication port for data reception (RX/DO) and transmission (TX/DI). In addition, the figure 4 shows a digital pin that is used to configure the module for use as a signal transmitter or receiver; this pin is called the data line enable (DE). To connect to the computer, the pins A and B of the RS-485 bus are used, connecting them to a USB adapter so that the signals reach one of its ports, and the program transfers the data directly to the chosen port. In the DAQ system, the communication module is used as a transmitter since it is required to send the data to the USB port.

4. Preliminary results for recording meteorological parameters

4.1. Irradiance recording

To relate the irradiance data from the mini-module and analog pyranometer with the reference instrument, is necessary to estimate a linear behavior between both sensors with a reference on a sunny day, as shown in figures 5 and 7 on the axis-x which present the voltage of both sensors. Using the linear behaviour, the irradiance that is impacted on the sensors is calculated through the equation of the linear fit. One method of validating compliance with the IEC standard is to use the root-mean-square error (RMSE) and the mean bias error (MBE), which are estimated in the equations (2) and (3), respectively. These equations determine a correlation between the data measured from the DAQ system ($M_{DAQ\ system_i}$) and the data from the reference system ($M_{ref\ system_i}$); these results are shown in tables 2 and 3 [8].

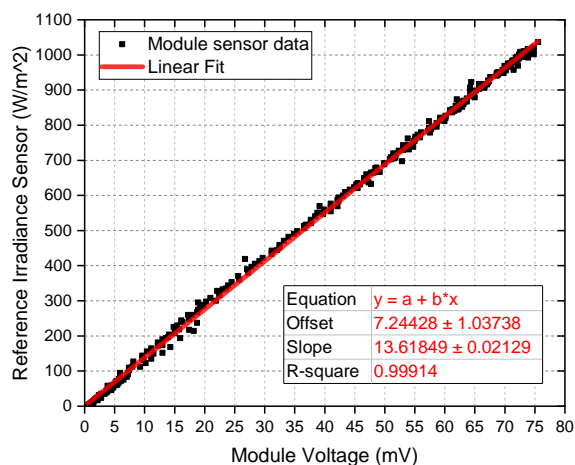


Figure 5. Voltage data from calibrated mini-module (mV) vs. reference irradiance sensor (W/m^2) (Measurements: 02/04/2020).

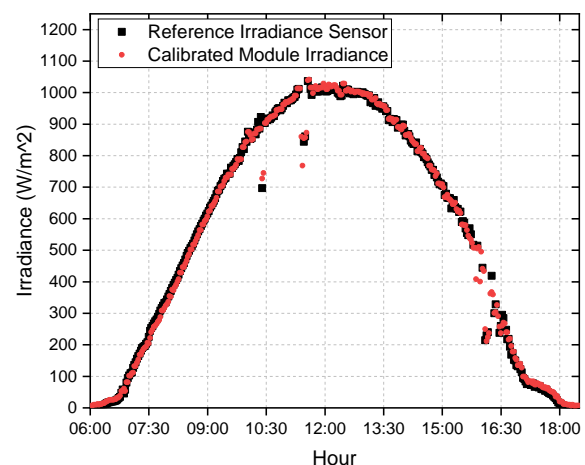


Figure 6. Irradiance comparison from reference irradiance sensor vs. calibrated module to estimate irradiation on a sunny day (Measurements: 02/04/2020).

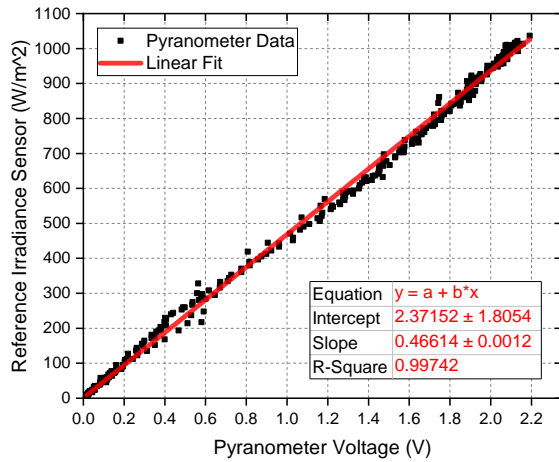


Figure 7. Voltage data from pyranometer (V) vs. reference irradiance sensor (W/m^2) (Measurements: 02/04/2020).

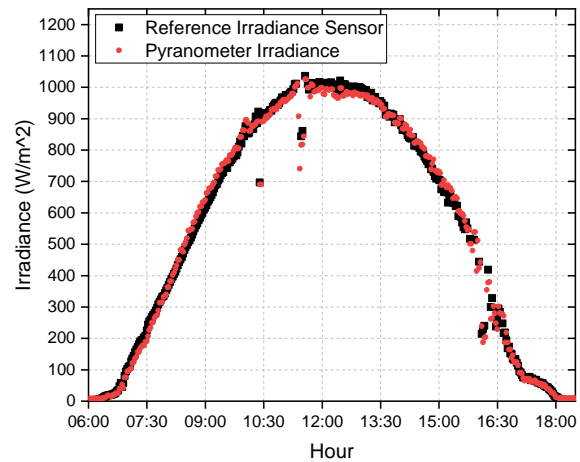


Figure 8. Irradiance comparison from reference irradiance sensor vs. pyranometer to estimate irradiation on a sunny day (Measurements: 02/04/2020).

Another method to validate the irradiation sensor’s correct measurement is to integrate under the curve of the instantaneous irradiance measurements and obtain the daily irradiation value, as shown in figures 6 and 8. The process is realized for the reference system with the measurements from the pyranometer and mini-module used in the DAQ system. The comparison of the irradiation values shows a negligible difference, as seen in table 2.

Table 2. RSME%, MBE% and irradiation comparison from irradiance measurements of DAQ system and referential sensor (Measurements: 02/04/2020).

	RMSE (%)	MBE (%)	Referential irradiation (kWh/m ²)	Measured irradiation (kWh/m ²)	Difference irradiation error (%)
Calibrated module	2	0.013	6.62	6.62	0.0032
Pyranometer	3.45	0.012	6.62	6.62	0.0041

4.2. PV module temperature recording

As a reference, we used a multimeter Keithley 2010 that measures the temperature with a thermocouple installed in the same position as the PT100. This reference allows us to validate the temperature data recorded by the DAQ system and estimate the measurement error of temperature, shown in table 3.

Table 3. RMSE% and MBE% from measured sensor by DAQ system and referential sensor which is measured by a calibrated multimeter (Measurements: 02/04/2020).

RMSE (%)	MBE (%)
1.95	0.00046

Figure 9 shows that the acquired data from the PT100 sensors present similar values to the reference measurement, except for a few outliers around 10:00 hours. The absolute error of the temperature parameters should not exceed 2 °C. Figure 10 shows a histogram with the temperature difference calculated with the reference data and the measured data from the DAQ system. Except for a few outliers, it is concluded that the temperature measurement does comply with the standard.

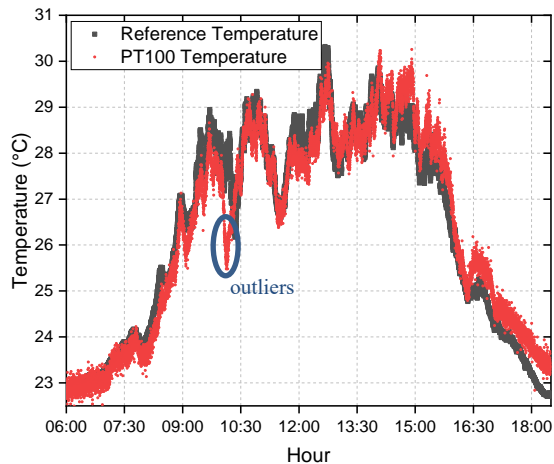


Figure 9. Temperature comparison from reference sensor vs. PT100 sensor in DAQ system to estimate the temperature average error (Measurements: 02/04/2020).

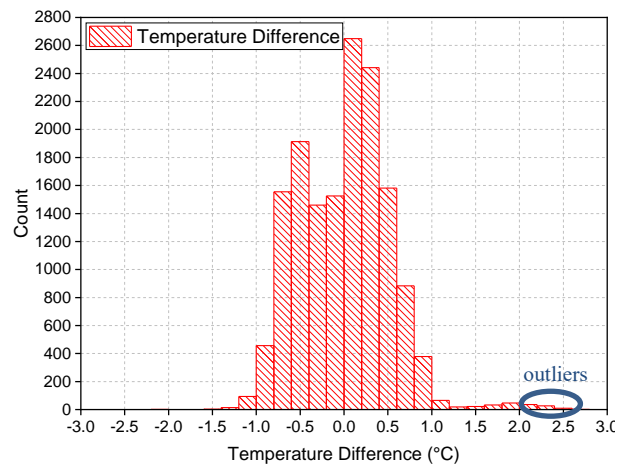


Figure 10. Histogram with differential temperature between measured and referential data to comply with the IEC Standard error (± 2 °C) (Measurements: 02/04/2020).

5. Conclusions

This article presented a design proposed for an open-source meteorological monitoring system for PV applications. This monitoring system allows the recording of values from analog sensors for irradiance and module temperature measurements. The monitoring system's design was described detailing each sensor with their signal converter used for recording irradiance and temperature of the PV module. Results of irradiance and module temperature measurements have been presented for 1 day to detect errors that could exist in the calibration of these parameters. From the values obtained, the reference yield value at the installation site can be estimated.

The system must operate according to the standards provided by IEC61724-1 to ensure correct yield estimates. Therefore, calibrated referential equipment was used to compare the measurements taken by the DAQ. Measurements obtained from irradiance data during calibration indicated an average error lower than 5%. Measurements of temperature by the acquisition system showed that, except for a few outliers, the measurements comply with the established error of ± 2 °C with respect to their calibrated reference. More detailed studies on the sources of error are required to ensure proper operation of the DAQ system and reproducibility measurements over a long time.

Finally, to analyze the measurement error in more detail, a calibration system allows controlling a simulated data output, which will help register the meteorological parameters in the DAQ system, complying with the IEC Standards and correct data calibration.

Acknowledgments

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References

- [1] Miranda C et al 2016 *La industria de la electricidad en el Perú: 25 años de aportes al crecimiento económico del país* (Lima: Osinergmin book) chapter 5 p 164
- [2] Aguirre C et al. 2017 *La industria de la energía renovable en el Perú: 10 años de contribuciones a la mitigación del cambio climático* (Lima: Osinergmin book) chapter 1 p 29
- [3] Schweiger M, Herrmann W, Gerber A, and Rau U 2017 Understanding the energy yield of photovoltaic modules in different climates by linear performance loss analysis of the module performance ratio *IET Renewable Power Gener.* **11**(5) pp 558–65
- [4] Fuentes M, Vivar M, Burgos J M, Aguilera J, and Vacas J A 2014 Design of an accurate, low-cost autonomous data logger for PV system monitoring using Arduino™ that complies with IEC standards *Sol. Energy Mat. Sol. Cells* **130** pp. 529-43
- [5] IEC 61724-1 2017 *Photovoltaic System Performance Part 1: Monitoring, 1st ed., International Electrotechnical Commission (IEC)* Switzerland
- [6] Lorenzo E 2014 *Ingeniería Fotovoltaica* (Sevilla) PROGNSA vol. 3 p 33
- [7] I. E. Commission, 2008 *Photovoltaic devices - Part 3: measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data, IEC 60904–3 ed2.*
- [8] Muñoz J V, Nofuentes G, Fuentes M, De la Casa J, and Aguilera J 2016 DC energy yield prediction in large monocrystalline and polycrystalline PV plants: Time-domain integration of Osterwald's model *Energy*, **114** pp 951-960
- [9] Louwen A, de Waal A C, Schropp R E, Faaij A P and van Sark W G 2017 Comprehensive characterisation and analysis of PV module performance under real operating conditions. *Prog. Photovoltaics Res. Appl.* **25** 3 pp 218-232.
- [10] Malvoni M, Leggieri A, Maggiotto G, Congedo P M and Giorgi M G 2017 Long term performance, losses and efficiency analysis of a 960 kW P photovoltaic system in the Mediterranean climate *Energy Conver. Manage.* **145** pp 169–81
- [11] Aguilera J and Espinoza R 2019 Feasibility evaluation of residential photovoltaic self-consumption projects in Peru *Renewable Energy*, **136** pp 414–427
- [12] Nole R 2013 *Diseño de un sistema de adquisición de datos utilizando el protocolo usb en un microcontrolador avr* (Lima: Bachelor thesis)
- [13] T. Kugelstadt 2008 *The RS-485 Design Guide Application Report The RS-485 Design Guide.*
- [14] I. E. Commission 1989 “*IEC 60529: degrees of protection provided by enclosures (IP code)*”, *See Append*
- [15] P. Semiconductors 2003 “*INTEGRATED CIRCUITS 2 C Manual I 2 C MANUAL Jean-Marc Irazabal-I 2 C Technical Marketing Manager Steve Blozis-I 2 C International Product Manager Specialty Logic Product Line Logic Product Group*”