UNIVERSIDAD POLITÉCNICA DE MADRID

**ESCUELA TÉCNICA SUPERIOR
DE INGENIERÍA Y SISTEMAS DE TELECOMUNICACIÓN**

**LOWERING UNCERTAINTY ON OUTDOOR
CHARACTERIZATION OF PV MODULES AND
CALIBRATION OF PV REFERENCE DEVICES**

TESIS DOCTORAL

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Ingeniero Técnico Industrial
Máster en Sistemas Electrónicos Avanzados**

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“El trabajo bien hecho, bien hecho está”
José Carrillo Requena

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RESUMEN

Los módulos y generadores fotovoltaicos se caracterizan midiendo su respuesta eléctrica en las llamadas Condiciones Estándar de Medida (CEM). Para ello, cuando se trata de módulos hay dos caminos bien diferenciados: la medida en simulador solar (capaces de imponer dichas condiciones) y la medida a sol real. En este último caso, hay que medir en condiciones ambientales de irradiancia y temperatura de célula y extrapolar los resultados.

Esta tesis se centra en la medida a sol real, buscando minimizar la incertidumbre. Para ello, y apoyándose en una amplia componente experimental llevada a cabo entre los años 2013 y 2017 tanto en el laboratorio exterior del GS-IES-UPM como en centrales fotovoltaicas comerciales, se proponen aquí los procedimientos siguientes:

- Reducir la incertidumbre en la calibración de la célula de referencia, combinando diferentes calibraciones independientes. El resultado final es una desviación estándar de 0,67%, siendo un 1,33% inferior a la que figura en el certificado de calibración original.
- Utilizar una “Caja Solar” aislada térmicamente para la medida de módulos patrones y para la calibración de módulos de referencia en laboratorio. Las incertidumbres a las que se ha llegado (desviación estándar de 0,935% en la potencia en CEM de los módulos, y de 0,93% en la irradiancia medida por los módulos de referencia) son del mismo orden que las de los mejores simuladores solares.
- Medir módulos fotovoltaicos manteniéndolos en la misma ubicación en la que trabajan (sin necesidad de desmontarlos de las estructuras de soporte), midiendo las condiciones de operación con un módulo de referencia razonablemente cercano (distancia inferior a 25 m) y corrigiendo la diferencia de temperatura existente entre el módulo de referencia y el módulo a ensayar. Con este procedimiento se ha llegado a una incertidumbre en la potencia en CEM de 1,94%, la cual es suficientemente buena para los controles de calidad realizados en el suministro de módulos fotovoltaicos.

ABSTRACT

PV modules and arrays are characterized by measuring their electrical response in the so-called Standard Test Conditions (STC). When it comes to PV modules there are two well differentiated ways: the measurement in solar simulators (able to impose such conditions) and the measurement at real sun. In the latter case, it is necessary to measure the environmental conditions of irradiance and cell temperature and to extrapolate the results.

This thesis focuses on the measurement at real sun, looking for minimize the uncertainty. To do this, and based on a large experimental component carried out between the years 2013 and 2017 both in the outdoor laboratory of GS-IES-UPM and in commercial PV plants, the following procedures are proposed:

- Reduce the uncertainty on the calibration of the reference cell, combining different independent calibrations. The final result is a standard deviation of 0.67%, being 1.33% lower than the provided in the original calibration certificate.
- Use a “Solar Box”, a thermally isolated device for the characterization of PV modules and for the calibration of PV reference modules in the outdoor laboratory. The uncertainties which have been reached (standard deviation of 0.935% on the STC power of the PV modules and 0.93% on the irradiance signal of the PV reference modules) are of the same order as those of the best solar simulators.
- Measure PV modules by keeping them in the same location in which they work (without disassembling them from the supporting structures), measuring the operating conditions with a reasonably close reference module (distance lower than 25 m) and correcting the temperature difference between the reference and the tested modules. With this procedure, the uncertainty reached on the STC power has been 1.94%, which is good enough to contractual power controls of PV modules supply.

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1. INTRODUCTION

From the proliferation of the firsts PV plants higher than 1 MW (beginning of XXI century)^[1] up to now, in which the largest PV plant has reached a power of 1 GW (Kurnool Ultra Mega Solar Park, India)^{[2], [3]}, the worldwide growth of PV plants has been exponential. In fact, from 2006 to 2016 the cumulative PV installed in the world has been almost doubled each 2 years (Figure 1)^[4]. Besides, forecasts have been met (Figure 2)^{[5], [6]} and the future ones go on with the same trends: in 2020 the PV installed power will be close to 500 GW_p, reaching 4600 GW_p in 2050.

Figure 1. Time evolution of global PV power installed from 2002 to 2016.

Figure 2. Accumulated PV power forecast for 2020, 2030 and 2050.

An increase so high was possible thanks to international agreements to promote a sustainable growth of the countries in order to preserve the environment^{[7]–[9]}. These agreements crystallized into policies for developing renewable energy sources, especially PV, which was benefited from favourable conditions to install large systems in addition to having juicy feed-in-tariff regulations to the energy coming from this technology^{[10], [11]}.

Nowadays it is considered that PV technology has already reached maturity and thanks to the technological improvements, which have made possible to reduce costs (mainly the drastic decrease in the PV module prices, Figure 3), PV installations are fully competitive in the framework of call for tenders, even unsubsidized with current levelized cost of energy (LCOE) between 42 and 52 €/MWh^[12]. Furthermore, just one year ago predictions even spoke of a LCOE below 40 €/MWh by 2030, lower than the current price of energy^{[13]–[15]}. So, PV installations can compete directly with other traditional energy installations in order to go on with its growth and development all around the world.

Figure 3. Evolution of the price of the PV module from 2000 to 2016.

In this context, PV systems are intensive on capital investment and engineering must assure the corresponding profitability looking for the actual energy productions match the expectations established on the design, in terms of energy production along the PV plant lifetime.

The energy yield estimation of a grid-connected PV plant is the result of a calculation on a scenario constituted by two types of assumptions: on the one hand, those that describe the operating conditions in a location, mainly the solar radiation and also the temperature. On the other hand, those that describe the constitution of the PV plant and its electrical response to these conditions. Table 1 summarizes the most relevant assumptions, which are the ones that provide the greatest uncertainty. Just minimizing the uncertainty on the characteristics of the PV arrays is the final goal of this work. It should be stressed that minimizing uncertainty directly translates into economic risk reduction which increases the general attractiveness for investors and the bankability of the PV plants.

Local weather	PV plant power response
Solar radiation: <ul style="list-style-type: none"> - Horizontal irradiation - Irradiance distribution - Fraction of diffuse irradiance Ambient temperature: <ul style="list-style-type: none"> - Temporal evolution 	Array: <ul style="list-style-type: none"> - Effective power at the inverter input - Variation of efficiency with irradiance and temperature Inverter: <ul style="list-style-type: none"> - Efficiency - Auxiliary consumption Operation: <ul style="list-style-type: none"> - Dirtiness - Aging

Table 1. Assumptions that lead to greater uncertainty in the energy yield estimation of a PV plant. Those corresponding to the array (bold type) are the main objective of this thesis.

PV modules and arrays are rated in the so called Standard Test Conditions (STC), defined as $G = 1000 \text{ W/m}^2$, $T_C = 25 \text{ }^\circ\text{C}$ and AM1.5, normal incidence. Hence, testing the PV power response to STC is a key aspect of any PV plant Quality Assurance Procedure (QAP). Besides, the relative change in efficiency associated with changes on temperature and irradiance are also relevant for energy production. Therefore, the determination of the corresponding coefficients is also of interest in QAP.

PV testing can be done in two different ways: indoors, using solar simulators which are able of imposing the STC conditions, and outdoors, translating to the latter the results obtained under arbitrary conditions. In this case, the precise determination of

such conditions is a paramount concern. In both cases, such response is obtained by tracing the I - V curve of the involved device.

1.1 PV MODULE CHARACTERIZATION

Indoor PV module characterization using solar simulators is more common than outdoor characterization at real sun. Solar simulators offer independence with respect to time and weather conditions. This represents an obvious advantage for both PV module manufacturers, who must test their products at the same production rate, and for specialized laboratories located in places which often have cloudy or polluted skies. For this reason, a solar-simulator industry offering well normalized products^{[16]–[18]} has been developed for years and many relevant players in the current field of PV now have this equipment. This has contributed to extending the common belief that highly-accurate PV measurements are easily taken by solar simulators. A symptom of this belief is the recent supply of mobile solar simulators^{[19]–[23]} for the indoor testing of PV modules on the PV plant sites.

A main disadvantage of solar simulators is its price, which can easily exceed 150000 € for an AAA type, the most accurate ones. This cost is large enough to dissuade many possible PV practitioners (universities, engineers, etc.) from trying to measure PV modules accurately, as required under due diligence for controlling the delivered power of PV modules supplies or for PV reference-module calibration. This is particularly annoying in many countries currently incorporating PV plants into their electric grid, but which lack specialized PV laboratories -Bolivia, Cape Verde, Equator, Kenya, Senegal, etc. are just a few examples. However, most of these countries often enjoy clear skies that represent an appealing alternative to accurate outdoor PV module testing. Moreover, the lack of solar simulators (except maybe during punctual periods: reception of PV modules from manufacturer, commissioning test, etc.) and clear skies are also typical circumstances at PV plant sites. Hence, developing methods for minimizing uncertainty on outdoor characterization of PV modules has been a key concrete objective of this thesis.

The outdoor measurement of PV electrical performance has been reported by widely-recognized laboratories, such as the Arizona State University's Photovoltaic Test Laboratory, The European Solar Test Installation, ESTI, at the European Commission's Joint Research Center^[24] and the Florida Solar Energy Center^[25]. All of them are dedicated to transferring I - V curves gathered under outdoor conditions to STC. All the corresponding analyses highlight that the major relative contribution to the uncertainty of the module power rating results comes from the calibration of the reference device (module or cell) used for measuring incident irradiance.

That led us, the *PV Systems Group* of the *Instituto de Energía Solar* of the *Universidad Politécnica de Madrid* (GS-IES-UPM), to proceed in two complementary ways. On the one hand, we have cross different independent calibrations of our reference device for reducing the corresponding uncertainty beyond the limits of any single calibration. On the other hand, we have designed and constructed the “Solar Box”, a home-made device simply consisting of a thermally-insulated box coupled to a temperature control system. Using this device, we are able to measure outdoors the electrical parameters at STC (or whatever other ones desired) and the temperature and irradiance coefficients.

Measuring with either solar simulators or solar boxes in existing PV plants requires handling the modules, taking out and putting on again from their operation positions at the supporting structures, which is an annoying and time consuming task (in addition to the possibility of PV module breakage during this process). Because of that, we have also explored the feasibility of testing while keeping the module in its original position on the structure. Having uncertainty minimization in mind, we have experienced with a concrete procedure consisting on the simultaneous measuring of two PV modules of the same type: the module under question and a previously calibrated reference one. That led us to design and make an original twin capacitive load^[26] and to perform different experiments in the roof of the facilities of our research group and in a large commercial PV plant. Mainly due to the dispersion of the module temperature among a same PV array, uncertainty tends to increase with the distance between the two modules. Aiming to compensate this fact we have tried different temperature measurement possibilities.

1.2 PV ARRAY CHARACTERIZATION

Testing large PV arrays (let us say of the order of hundred kW) must obviously be done outdoors and it is generally taken with a lot of caution in current PV engineering practices. Mainly because instantaneous temperature dispersion can be large, power measurements are suspicious of also have large uncertainty and the study of the performance of these arrays is typically trusted to energy (not power) observations along representative periods. The weekly Performance Ratio (PR), nowadays extensively applied in the commissioning testing of technical due diligences imposed by bank financing, is a well-known example. Interestingly, the IEC-62446^a clearly specifies *“The values measured in the field should be compared with the expected values. The comparison with the expected values is performed as evidence of correct installation, not as a measure of the performance of the module or array. Verification of module/array performance is beyond the scope of this standard”*. In coherence with all these cautions, the I - V tracer industry limits the maximum power of its products to about 100 kW^{[27]–[30]}.

However, we still think that measuring I - V curves of large arrays is an exciting task that can yield significant benefits for PV engineering. Following a tradition of large I - V curves in our research group, that led to measuring a 500 kW and an 800 kW I - V curves on 2012^{[31], [32]}, we have designed and constructed an I - V tracer able of dealing with up to 2 MW and we have effectively measured I - V curves larger than 1 MW, which represent the current world record for power measurement in characterization of PV arrays.

^a IEC 62446: Grid connected photovoltaic systems. Minimum requirements for system documentation, commissioning tests and inspection.

1.3 PV REFERENCE MODULES

Whichever the case, outdoor PV testing requires measuring solar irradiance and module temperature. When the goal is to characterize a PV module or to analyse the performance of a PV array, the lowest uncertainty is obtained with irradiance sensors that have the same spectral, angular and thermal response that the object under test. Such sensors can be single modules of the same type of the concerned object, previously stabilized and calibrated in short-circuit current, for irradiance, and/or in open circuit voltage, for temperature.

Such reference modules are not standard commercial products. Instead, they must be specifically prepared for each PV plant, which is one of the services offered by the GS-IES-UPM. In the works of this thesis, we have paid particular attention to the estimation of the uncertainty on the measurements with PV reference modules, being able of relating the uncertainty with the irradiance incident angle.

1.4 THE THESIS CONTEXT

The underlying works of this thesis have been carried out in the GS-IES-UPM, mainly in the framework of the technical services provided by this group to the PV industrial sector. The history of outdoor measurements of commercial PV modules in this group started as soon as 1992 in the context of the Toledo-PV plant^[33], that was the first European PV system reaching the MW scale^{[34]–[36]}. The GS-IES-UPM was in charge of the power control of the PV modules supply. For that, an I - V tracer based on bipolar transistors was built (Figure 4) and accurate outdoor power measurements were achieved by quasi-simultaneous measuring of two modules: a reference one (previously calibrated by the *Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas* – CIEMAT) and the module under test. Besides, a capacitive I - V tracer (based on thyristors) was made for measuring PV arrays, achieving I - V curves of up to 40 kW. Operation conditions were measured by means of reference PV modules (again calibrated by CIEMAT).

(a)

(b)

Figure 4. (a) I - V tracer based on bipolar transistors and capacitors. (b) I - V curve corresponding to a measurement of a PV module in the Toledo's PV plant on December 17th, 1992.

A relevant chapter of this little history happened 20 years later. Between 2007 and 2008, the so called “*Spanish's boom*”, led to the installation of about 3 GW of large PV plants under the umbrella of bankability and relatively strict technical quality controls. Taking advantage of this opportunity, the GS-IES-UPM was involved in the testing of about 40 PV plants, with a cumulative power of around 200 MW^[37]. For that, many PV reference modules were prepared (for simultaneously measuring both irradiance and cell temperature with only one module) and calibrated, and a new capacitive load, this time based on IGBT's^[38] (Figure 5), was constructed and I - V curves up to 800 kW^[32] were recorded.

Figure 5. First capacitive I - V tracer based on IGBTs implemented by GS-IES-UPM.

The provision of testing and other technical services to large PV plants keeps going on from the *PV Spanish's boom* period, expanding to the international scene. The

works supporting this PhD thesis have just coincided with this time. A commercial PV plant has been of particular interest. In *El Romero Solar* PV plant, of 246 MW_p of power and located in the Atacama Desert (Chile), some tests have been carried out to determine the uncertainty on the characterization of PV modules in the field, as well as different measurement procedures to reduce the uncertainty due to the dispersion of temperature in the PV arrays.

In addition, since 2013 we have characterized about 400 PV modules inside the constructed Solar Box, many of them to be used as reference modules to measure the effective irradiance^b, G_{ef} , and the solar cell temperature, T_C , in quality assurance procedures for large commercial crystalline silicon PV plants^{[39], [40]}.

Regarding PV technology, the current large PV plants scene is strongly dominated by flat modules made with crystalline silicon solar cells and most prospective studies coincide on that is going to continue in the years to come^{[4], [6], [11], [14], [41], [42]}. Hence, we have restricted our work just to this technology. Possible alternatives like thin-films or concentrators are not considered in this thesis.

1.5 OBJECTIVES

The general goal of this thesis is to contribute to minimizing uncertainty on the characteristics of the PV arrays. This has materialized in five concrete objectives:

- Reducing the calibration uncertainty of the GS-IES-UPM reference device for measuring irradiance below the values associated to standard single calibrations.
- Developing methods for accurate outdoor characterization (in terms of STC power and also temperature and irradiance coefficients) of single modules.

^b The effective irradiance, G_{ef} , is the irradiance that effectively contributes to the generation of electricity.

- Analysing the uncertainties along all the GS-IES-UPM testing chain.
- Constructing capacitive loads for specific purposes: a twin capacitive load for simultaneous measuring of two PV modules, and a big load for measuring I - V curves up to 2 MW.
- Exploring methods for in-field STC power characterization of PV modules.

In the next chapters of this document are presented the tests done to achieve these objectives, as well as the devices which have been developed and implemented to perform such tests.

So, chapter 2 presents the instrumentation needed to perform the characterization of PV modules/arrays and the calibration of PV reference devices.

On chapter 3 can be seen the results of different tests and the calibration - characterization procedures carried out in the laboratory of the GS-IES-UPM with high accuracy and low uncertainty.

Chapter 4 reports about the results and uncertainties obtained on the measurements in large PV plants.

On chapter 5 the main conclusions of the work are presented. Also future research lines are suggested.

Appendix A provides an explanation of what is uncertainty and how to calculate it.

Finally, Appendix B shows the results of the Type A uncertainty on the outdoor measurements of PV modules.

2. INSTRUMENTATION

2.1 INTRODUCTION

This chapter describes the instruments developed on this thesis. Their need has been justified at the introductory chapter. On the one hand, we have made two capacitive I - V tracers: a twin load for simultaneous measuring of two PV modules, and a big load for measuring I - V curves up to 2 MW. Hence, they are aimed for specific purposes that are not covered by current commercial products^{[28], [29], [43]}. Besides, own manufacture allows for adapting the I - V tracer characteristics, for example the capacitor charging time, to the particular testing case. On the other hand, we have made a “Solar Box” for the testing of PV modules. This box allows imposing a desired temperature at the beginning of exposing the module to the sun. That paves the way for outdoor measurements at irradiance close to 1000 W/m² and temperature ranging from 25 °C to more than 50 °C, thus allowing characterizing the module in STC power and also in temperature coefficients.

2.2 CAPACITIVE LOADS

The underlying idea of a capacitor I - V tracer, usually also referred as capacitive load, is to take advantage of the voltage evolution of a capacitor during charging for sweep the I - V curve of a PV device. For that, an initially discharged capacitor is directly connected to the PV device under test while it is exposed to the sun. The schematic of an ideal capacitive load is shown in Figure 6a, and its main components are a switch and a capacitor. If the capacitor is initially discharged (0 V) and the switch closes up, the generator delivers its short-circuit current and the capacitor charge starts. Then, the voltage increases and the current decreases from the short-circuit point to the open circuit point ($I = I_{SC}$, $V = 0$ to $I = 0$, $V = V_{OC}$), as can be seen in Figure 6b.

Figure 6. (a) Ideal capacitive load composed of a switch and a capacitor. (b) Current and voltage waveforms after closing the switch in $t = 0$.

Assuming that the PV array curve can be approximated by an ideal rectangular I - V curve represented in Figure 7, the capacitor charging time, t_c , depends on its capacitance, C , and on the instantaneous values of I_{sc} and V_{oc} according the next equation^[44]:

$$t_c = \frac{V_{oc}}{I_{sc}} C \quad (1)$$

Figure 7. Ideal (continous line) and real (dotted line) I - V characteristics of a PV array.

The actual charging time is slightly higher than the value given by this equation because the fill factor, FF , is lower than unity. The size of the capacitor is selected according to the required charging time, whose recommended value is between 20 and 200 ms in order to avoid the variation of the operating conditions during the tests (slower charging times) and the capacitance effects on the PV module^[45], as it is shown in Figure 8 (faster charging times): when capacitors which lead to charging times lower than 10 ms are selected, the I - V curve obtained shows an undesired variation in its

quasi-horizontal region of the shape. This mistake during the measurement process does the maximum power obtained is higher than the real one.

Figure 8. Capacitance effects observed in a PV module due to charging times faster than 20 ms.

Table 2 displays the ranges of the ratio V_{OC}^*/I_{SC}^* for different commercial PV modules^[42], and the calculated ranges for C assuming equation (1) and $t_C = 100$ ms. Needless to say, the switch device and the capacitor must be selected in coherence with I_{SC}^* and V_{OC}^* , respectively.

Technology	V_{OC}/I_{SC} range (under STC) (Ω)	Maximum V_{OC} (under STC) (V)	C (mF)
Mono x-Si	3-12	64	8-33
Poly x-Si	2-22	80	5-50
a-Si single junction	60-120	140	1-2
μ c-a-Si	18-144	174	1-10
Cd-Te	19-34	61	3-5

Table 2. Ranges of the ratio V_{OC}^*/I_{SC}^* of commercial PV modules whose nominal power is between 50 and 300 W_p , and the approximated ranges for the capacitor size assuming a charging time of 100 ms.

In order to prepare the load for a new measurement, the capacitor must be discharged at the end of the previous one. For that, the capacitor is disconnected from the PV device and connected to a discharging resistor. The discharging process has

neither current nor time restrictions, so that the corresponding switch and resistor can be free selected. According with our experience, discharging times as large of several seconds, which encompasses low discharging currents and also low dissipated powers, still allow for comfortably repeating measurements.

Another relevant aspect for practical designs results from considering that the wiring that connects the PV device to the capacitor has a non-null resistance. That makes the PV device voltage to be somewhat larger than the capacitor voltage. To avoid this problem, I and V measurement must be done in accordance with the four-probe concept (also known as four-point Kelvin probes), in order to properly record the voltage at the PV device. Besides, the capacitor must be slightly negatively pre-charged, in order to assure crossing the short-circuit point. Finally, the load must be protected against reverse polarity, and each one of the power circuits (respectively for charge and discharge) must be driven by a control circuit avoiding bouncing and providing safe electrical insulation from the power circuit. Next section gives further details of our practical designs.

2.2.1 THE TWIN CAPACITIVE LOAD

A twin capacitive load results just for the duplication of a single capacitive one with the caution of sharing both the pushing button for starting charging or discharging process and the pre-charging circuit. Figure 9 and Figure 10 present the schema of the twin capacitive load we have made.

The functions of the components of the power circuit are the following:

- $IGBT1$ and $IGBT2$ are switched ON-OFF sequentially for charging and discharging, respectively, the capacitor C .
- The current of the PV modules are measured through the voltage drop in the calibrated resistors, R_{SHUNT} .

- Diode D_1 protects the load against the reverse polarity connection of the PV module.
- The negative pre-charging circuit applies a negative voltage ($V_B = -9$ V) to the capacitor, ensuring that the I - V characteristic starts in the second-quadrant ($V < 0$, $I > 0$) and crosses the short-circuit point^[46]. The fuse F_2 protects the pre-charging circuit against the possibility of pushing the button $P1$ without performing a previous discharge of the capacitors (it is necessary to ensure that the capacitors voltages are lower than ≈ 5 V before beginning the negative pre-charging process). R_P limits the current through said circuit.
- The fuse F_1 protects the $IGBT2$ against the direct connection of the PV module, which may occur in the case of an eventual failure of the $IGBT1$.
- The resistor R_D allows the capacitor C to be discharged when the $IGBT2$ is switched ON.
- Finally, diode D_2 is used to avoid the discharge of the capacitor C through R_D and the diode of the $IGBT2$ when the negative pre-charging voltage has been applied.

Figure 9. Power circuit of the twin capacitive load. As the power circuit is symmetric, subscript "R" reports about the part of the circuit related to the measurement of the reference module while subscript "T" reports about the part of the circuit related to the measurement of the test module.

The main components used in the power circuit are given in Table 3.

Component	Description	Electrical characteristics
IGBT1, IGBT2	Discrete IGBT SGP30N60	30 A / 600 V
C	Aluminium electrolytic capacitors	6.8 mF / 200 V
D1	Rectifier diode	20 A / 600 V
D2	Rectifier diode	5 A / 600 V
F1, F2	Fuse	2 A
RP	Resistor	10 Ω / 10 W
VB	Dry cell	9 V
RSHUNT	Calibrated resistor	10 A / 150 mV (15 m Ω)

Table 3. Power circuit components of the twin capacitive load.

The control circuit has been improved on regards the previous one^[38] using a better debounce circuit (R_1 - R_2 - C_1 network plus inverter) and providing a safe optical insulation between the power and control circuits (optocoupler). The switch placed on the left-hand side of Figure 10 is used to select the charge (*IGBT1*) or the discharge (*IGBT2*) of the capacitor, and the “Push” button switches ON the selected *IGBT* (1 or 2) when it is pressed.

Figure 10. Control circuit of the twin capacitive load.

The components used in the control circuit are presented in Table 4.

Component	Description	Electrical characteristics
C_1	Capacitor	1 μF / 63 V
D_{Z1}, D_{Z2}	Zener diode	18 V / 1 W
Inverter	Schmitt-Trigger Inverter SN74HC14	
Optocoupler	5.0A Gate Drive Optocoupler ACNW3190	
R_1	Resistor	1 k Ω / 0.5 W
R_2	Resistor	22 Ω / 0.5 W
R_3	Resistor	330 Ω / 0.5 W
R_G	Resistor	10 Ω / 0.5 W
R_{GE}	Resistor	47 k Ω / 0.5 W

Table 4. Control circuit components of the twin capacitive load.

Figure 11 shows some pictures of the final equipment. It integrates 2 voltmeters for monitoring the voltage at the capacitors. I and V signals are measured by a 12 bit-digitization oscilloscope with four isolated channels, which prevents noise, and a sampling frequency of 5 MS/s. The data are then transferred via USB interface to a PC for further treatment, which includes digital filtering^{[47]–[49]} by selecting the first 40 coefficients of the Discrete Fourier Transformer for both sequences of I and V , and a curve translation to STC. G and T_C are derived from the I_{SC} and V_{OC} of the reference module. The materials cost has been about 1100 € (power circuits, 150 €; control circuits, 160 €; wiring, connectors, switches, etc., 450 €; box and dust protectors, 150 €; calibrated resistors, 100 €).

(a)

(b)

Figure 11. Current aspect of the twin capacitive load. (a) PC, multimeters to monitor the voltage of the capacitors and twin capacitive load ready for measurement. (b) Internal view of the twin capacitive load.

As a representative example, Figure 12 shows the results of the measurement of a PV module using the twin capacitive load, where the currents and voltages of the reference and sample modules are represented as a function of time. Charging time is about 45 ms and up to 10000 I - V points are recorded during the process. The sharp peak current observed at the starting is a transitory current due to the displacement of majority carriers at both sides of the P-N junction of the solar cells to accommodate the depletion region change when the PV module, initially in open circuit, is suddenly put on short-circuit. This is merely anecdotic for module characterization and is disregarded during further treatment.

Figure 13 shows a typical report with which the GS-IES-UPM presents the results of the I - V curve measurements of a PV module. In this case, the report details the results of the direct measurements carried out on November 10th, 2015 in the outdoor laboratory of the research group, as well as its extrapolation to STC according to the IEC-60891. As a summary, the final values of the characterization (Figure 13 - right) and the measured and extrapolated to STC I - V curves (Figure 13 - left) are presented.

Figure 12. Current and voltage of two PV modules as a function of time, which have been registered during the charge of the capacitors using a differential four-channel oscilloscope.

DESCRIPTION

DATE (dd/mm/yyyy) **10/11/2015**
 SITE **IES-UPM (Vallecas, Madrid)**

TEST **I-V characteristic of the PV module**

PV REFERENCE MODULE **MY3.1 (104301028390)** **(IES - internal reference)**

PV MODULE TO CHARACTERIZE

IDENTIFIER (Serial Number)	4120701700221						
PV MODULE	NOMINAL CHARACTERISTICS (nameplate)						
Manufacturer	Trina Solar	I_{SC}^* [A]	V_{OC}^* [V]	I_{MPP}^* [A]	V_{MPP}^* [V]	P_{MPP}^* [W]	FF^*
Model	TSM-235PC05	8.31	37.10	7.81	30.10	235.00	0.762

MEASUREMENTS

	DIRECT				EXTRAPOLATED TO STC			
HOURLY	14:30	14:31	14:32	14:33	14:30	14:31	14:32	14:33
G [W/m ²]	913	910	908	908	1000	1000	1000	1000
T_c [°C]	52.3	51.9	51.7	51.8	25.0	25.0	25.0	25.0
I_{SC} [A]	8.05	8.01	8.00	8.00	8.71	8.71	8.72	8.72
V_{OC} [V]	32.94	32.95	32.96	32.94	36.37	36.34	36.34	36.32
I_{MPP} [A]	7.36	7.36	7.34	7.35	8.09	8.08	8.08	8.09
V_{MPP} [V]	25.60	25.54	25.56	25.51	29.11	29.08	29.06	29.05
P_{MPP} [W]	188.61	187.94	187.57	187.49	235.42	234.99	234.79	234.85
FF	0.712	0.712	0.711	0.711	0.743	0.742	0.741	0.742

Figure corresponding to the measurement of 14:30

SUMMARY

	AVERAGE $\pm \Delta$ (Significance level 5%)			Deviation of the nominal value [%]
I_{SC}^* [A]	8.72	$\pm$	0.02	4.9
V_{OC}^* [V]	36.34	$\pm$	0.07	-2.0
I_{MPP}^* [A]	8.09	$\pm$	0.02	3.5
V_{MPP}^* [V]	29.08	$\pm$	0.08	-3.4
P_{MPP}^* [W]	235.01	$\pm$	0.90	0.0
FF^*	0.742	$\pm$	0.003	-2.6
P_{MPP}^* with γ [W]	233.58	$\pm$	0.95	-0.6

COMMENTS

- Temperature coefficient of I_{SC} $\alpha = 0.05\%/^{\circ}\text{C}$, according to the manufacturer datasheet.
- Temperature coefficient of V_{OC} $\beta = -0.32\%/^{\circ}\text{C}$, according to the manufacturer datasheet.
- Temperature coefficient of P_{MPP} $\gamma = -0.43\%/^{\circ}\text{C}$, according to the manufacturer datasheet.

Figure 13. Typical report with which the GS-IES-UPM presents the results of the I-V curve measurements of a PV module (left) and its extrapolation to STC in accordance with the IEC-60891 (right). The figure represents the first measurement (blue) and its extrapolation to STC (orange).

2.2.2 THE 2 MW CAPACITIVE LOAD

This equipment uses the same control circuit described before (Figure 10) while the power circuit has been adapted to currents up to 2500 A and to voltages up to 1200 V. Figure 14 presents the corresponding scheme. The special components that are used for this load are the following:

- *IGBT1*, is composed of two IGBTs in parallel to allow much greater current measurement and acts as a switch for the charging process.
- *M1* is a magnetothermic protection for *RD* against the direct connection of the PV array, which can occur if the *IGBT1* breaks down.
- *C* is the sum of 9 electrolytic capacitors (able of working at high voltages) connected in 3 parallel associations of 3 capacitors in series. Another group of 9 capacitors with the same distribution will be added in the case it is needed to modify the charging time (to double it).

Figure 14. Power circuit of the 2 MW capacitive load.

The electrical characteristics of all the components of the capacitive load are displayed in Table 5. Figure 15 shows some pictures of the final equipment.

Component	Description	Electrical characteristics
C1 to C9 and C10 to C18	Aluminium electrolytic capacitors	400 V / 21000 μ F (each one)
D1	Rectifier diode	16 A / 400 V
D2	Rectifier diode VS-150U100D	150 A / 1000 V
M1	Magnetothermic switch	3 A / 60 $^{\circ}$ C
IGBT1	IGBT module FUJI 1MBI900V-120-50	900 A / 1200 V (each one)
IGBT2	IGBT module MG100Q2YS50	100 A / 1200 V
RD	Power resistor	1 k Ω / 300 W
F1	Fuse	1 A
RP	Resistor	10 Ω / 25 W / 160 V
VB	Negative pre-charging voltage	Dry cells, 18 V
RS	Precision resistor	Internal: 60 mV / 100 A (0.6 m Ω) 60 mV / 200 A (0.3 m Ω) External: 150 mV / 1000 A (0.15 m Ω)

Table 5. Power circuit components of the 2 MW capacitive load.

In order to facilitate the transport, the load has been divided in three isolated boxes (one box for the power and control circuits, and two boxes for the capacitors). In addition, a remote control has been added to handle the load at a certain distance for safety reasons (Figure 15e). The total cost of the 2 MW load is about 5000 € (power circuit, 700 €; capacitors, 2100 €; control circuit, 150 €; isolated boxes, 1600 €; wiring, connectors and calibrated resistors, 500 €).

Using this load we have measured I - V curves of more than 1 MW (see section 4.4).

(a)

(b)

(c)

(d)

(e)

Figure 15. External and internal views of the 2 MW capacitive load boxes. (a) Isolated boxes. (b) Capacitors. (c) Drivers and power circuit. (d) Control panel and remote control. (e) Remote control to handle the capacitive load from a safe distance.

2.3 THE “SOLAR BOX”

This rather simple home-made device (Figure 16) consist on a 2.10x1.80x0.33 m (length x width x height - internal dimensions) thermally-insulated wooden box with polystyrene and equipped with a standard air-conditioning system. The box is mounted on a metallic structure that can be manually positioned in both azimuth and tilt. A working reference solar cell, coplanar but external to the box, provides a first approximation to the incident irradiance while the box is still closed.

The measurement procedure with the Solar Box is as follows: the PV module is placed inside the box in such a way that the air-gap between the PV module surfaces (back-sheet and front-glass) and the inner box surfaces is about 15 cm, which ensures easy air circulation^[50]. Then, the box is oriented until the external cell indicates an irradiance value close to 1000 W/m^2 (according to our experience, $\pm 5\%$, which is easy to obtain, suffices). Meanwhile, the air conditioning system maintains an inside temperature which is slightly lower than $25 \text{ }^\circ\text{C}$ (quite often by cooling it down). Four fans located in the corners of the internal box help to homogenize the temperature^[51]. Then, the front cover of the box is removed and 25 I - V curves^c, equally spaced on time, are obtained throughout the PV module's natural heating process, which takes about 20 minutes. 9 PT1000 sensors glued to the backsheet of the PV module measure the temperature of the solar cells. The effective irradiance is accurately measured simultaneously by means of a carefully calibrated reference cell (section 3.2) placed inside the box. This reference cell is a monocrystalline silicon sensor, short-circuited through a high stability resistor, in such a way that the cell provides a voltage signal (which is recalibrated annually).

^c Due to the linearity of the results obtained, 25 I - V curves are not necessary. Just 15 I - V curves are enough.

Figure 16. Solar Box developed by GS-IES-UPM used for testing PV modules outdoors. (a) Solar Box covered. (b) Solar Box opened. The figure shows the external and internal reference solar cells, the four fans to homogenize the temperature inside the box before it is opened, the air conditioning and the module inside, prepared to be measured at STC.

The I - V curves are obtained by means of one half of the twin capacitive load described above. Data from the reference cell and from the PT sensors are stored synchronously using a datalogger (20-bit digitization). The average of the corresponding 9 temperature values, once corrected by $+3\text{ }^{\circ}\text{C}$ to compensate the drop in back-skin-to-cell temperature^{[52]–[54]}, is considered to be the true PV module temperature. Strictly speaking, such $+3\text{ }^{\circ}\text{C}$ temperature correction is only valid in thermal equilibrium, so that its validity in the situation after the cover has been lifted and the module is warming up can be questioned. However, applying such correction leads to V_{OC}^* values that agree well (better than 0.4%, as we will see in section 3.3.4.4) with the values measured at pulsed solar simulators which are free of the drop in cell-to-back-skin temperature effect. That is the main reason leading us to keep the correction even in that situation.

In order to minimize corrections and uncertainty, the measurements are validated just if $G_{ef} \geq 900\text{ W/m}^2$ and the temperature between the hottest and the coldest point of the PV module (as given by the 9 PT1000) differs by less than $3\text{ }^{\circ}\text{C}$ at the beginning of the procedure (when testing the STC characteristics) and by less than $7\text{ }^{\circ}\text{C}$ throughout the rest of the process (when testing the temperature coefficients). That makes our measurements comply with international standards^{[46], [55], [56]}. Corrections to STC are made in accordance with IEC-60891. In fact, our conditions are even more restrictive than that demanded by the norm. For example, IEC-60904-4 requires $G_{ef} \geq 800\text{ W/m}^2$

and we impose $G_{\text{ef}} \geq 900 \text{ W/m}^2$; IEC-60891 requires the temperature to be measured at 4 positions, however we measure it at 9 positions. As the tested PV modules and the work reference cell are of equivalent technology (c-Si), possible spectral corrections are completely disregarded. Measurements should be performed just on clear days, so that the irradiance keeps essentially constant along the 20 minutes process.

Besides, in order to make further research possible, collateral information could be also recorded: barometric pressure provided by a meteorological station on the measurement site and the spectral related data (Aerosol Optical Thickness, water vapor and Angstrom parameter^[57]).

Finally, it should be mentioned that the Solar Box materials cost is only about 1500 € (wood, 80 €; insulation, 40 €; fans, 50 €; support structure, 850 €; reference cell, 500 €). This box must be used in combination with additional components (a laptop computer, a capacitive load, an external working cell, an air-conditioning system and temperature sensors), that cost must be also taken into account. The total cost is, approximately, 4500 €. Besides, this device can be easily implemented wherever the PV plant is installed to perform accurate on site characterizations of PV modules (if required precautions are taken into account^[47]: have an $G > 600 \text{ W/m}^2$, a diffuse fraction less than 20 %, wind speed less than 5 m/s), avoiding the cost related to transport them to specialized PV laboratories located far away and the decreasing the possibility of module damage during this return voyage.

3. LABORATORY MEASUREMENTS

3.1 INTRODUCTION

This chapter describes the experience with PV modules measurements at the outdoor GS-IES-UPM facilities located in Madrid (Campus Sur UPM). With the common aim of minimizing and estimating uncertainty we have performed the following tasks: calibration of the reference cell for measuring irradiance, PV module characterization on the Solar Box and measurements of irradiance and module temperature with reference modules. Besides, looking for exploring in-field testing possibilities of direct application in commercial PV plants, we have compared different PV measurement possibilities without the help of the Solar Box. APPENDIX A explains the basic concepts about uncertainty^[58], which can be useful to a better understanding of this chapter.

3.2 CALIBRATION OF THE REFERENCE CELL

As recognized by other authors^{[24], [25]}, the main contribution to uncertainty in PV module characterization comes from the reference cell used for measuring irradiance and linking the traceability of our calibrations to the International System of Units (S.I.). This is why we have paid particular attention to the calibration of this device. Our reference cell is a c-Si one (ISET sensor), acquired in 2013 from IKS Photovoltaik. It provides an irradiance signal (from an internal resistor, short-circuiting the cell) and a temperature signal (from an internal PT1000). The cell was delivered with a calibration certificate from the Fraunhofer-ISE (2626-13). The calibration value is $92.025 \text{ mV}/(\text{kW}/\text{m}^2) \pm 4\%$ ($k=2$)^d with the cell at 25 °C. Furthermore, the instruction

^d The coverage factor, k , is associated with the confidence interval (APPENDIX A).

manual of the ISET sensor says that the temperature coefficient for irradiance is $0.065 \pm 0.015 \text{ }^\circ\text{C}$.

As this cell plays a key role in our measurement uncertainties, we have paid particular attention to its calibration, submitting it to the three additional calibration procedures as summarized in Table 6. In all the cases the initial calibration value is given by the slope of the direct irradiance signal of the solar cell plotted against the irradiance seen by a coplanar reference device traceable to the S.I.. Now, appropriate angular, spectral and temperature corrections must be applied to take into account the difference among the calibration procedures.

Independent calibrations						
Date	Calibration body	Initial calibration		Procedure	Corrected calibration	
		Value (mV/(kW/m ²))	Standard deviation (%)		Value (mV/(kW/m ²))	Standard deviation (%)
March 2013	FISE	92.025	2	At a solar simulator against a reference cell	92.025	2
July 2014	CIEMAT	90.4	1	At natural sunlight against the global irradiance given by a pyranometer	90.354	1.459
May 2015	5th International Spectro – and Broadband Radiometer Intercomparison	90.84	0.87	At natural sunlight against the global irradiance given by a cavity pyrheliometer and a shaded pyranometer	90.796	0.988
February 2017	GS-IES-UPM	91.384	1.05	At natural sunlight against a reference cell calibrated by NREL	91.089	1.445
March 2017	Final assigned calibration				90.899	0.67

Table 6. Calibration procedures carried out by different laboratories. Likewise, the initial calibration values are also shown with their respective uncertainties ($k=1$) and corrected for temperature, angle and AM.

The FISE calibration was carried out on a solar simulator against a c-Si primary reference cell which, in turn, was calibrated at the PTB^[59] by means of the so-called DSR calibration method^[60]. In both calibration steps all the light is inside the angle of

acceptance of the concerned cell ($\approx 60^\circ$). Furthermore, the cell temperature is kept at 25°C . No corrections are needed.

At the 5th International Spectro – and Broadband Radiometer Intercomparison, the calibration was carried out on days with clear sky conditions. The solar cell, three cavity radiometers (for direct irradiance traceable to the WRR^[61], having a combined uncertainty of 0.103% ^[62]) and a shaded pyranometer (for diffuse irradiance, calibrated by the sun and shade method against the cavities and having an uncertainty of 0.78%) tracked the sun. This is somewhat close to the so-called global sunlight method for primary photovoltaic reference cells^[63]. The measuring campaign was carried out in Madrid, from May 18th to 22th 2015. The calibration period was within ± 3 hours around midday and that AM-corrected pressure ranged from 1.0 to 1.6. The result (after the appropriate filtering: $G > 800 \text{ W/m}^2$, difference between cavity radiometers $< 1 \text{ W/m}^2$) is a set of more than 700 valid measurements, each one made up of four values: the irradiance signal of our cell, the direct irradiance given by the cavities, the diffuse irradiance given by the shaded pyranometer and the ambient temperature. Unfortunately, the temperature signal of our cell was not stored. The standard deviation of the initial calibration is 0.87% (Type A: 0.86% and Type B: 0.10%). However, the angle of acceptance of the pyranometer ($\approx 90^\circ$) is larger than that corresponding to the cell. An angular correction is divided into two steps. First, considering that the diffuse irradiance has two components: one isotropic, D^I , and another circumsolar, D^C . According with Hay^[64], the isotropic component can be estimated as:

$$D^I = D \left(1 - \frac{B}{B_0 \varepsilon_0} \right) \quad (2)$$

where B_0 and ε_0 are, respectively, the solar constant (1367 W/m^2) and the eccentricity factor of the day. The ratio D^I/D on the results of the measuring campaign ranges from between 0.24 and 0.40. Second, considering that the ratio between the isotropic irradiance seen by two devices with acceptance angles α_1 and α_2 is:

$$\frac{D_{\alpha_1}^I}{D_{\alpha_2}^I} = \left(\frac{\sin \alpha_1}{\sin \alpha_2} \right)^2 \quad (3)$$

In our case, $\frac{D_{\alpha_1}^I}{D_{\alpha_2}^I} = 0.75$. Furthermore, a spectral correction for the direct irradiance can be derived using the empirical polynomial regression between AM and the relative short-circuit response, considered at the so-called SANDIA PV performance model^{[65], [66]}.

$$I_{SC}(AM) = I_{SC}(1.5) \times f(AM) \quad (4)$$

$$f(AM) = a_0 + a_1 AM + a_2 AM^2 + a_3 AM^3 + a_4 AM^4 \quad (5)$$

where a_0 to a_4 are empirical coefficients for each particular PV device. We have used typical values from the SANDIA module database^[67] for c-Si modules: $a_0 = 0.9315$, $a_1 = 0.05975$, $a_2 = -0.01067$, $a_3 = 0.0008$ and $a_4 = -0.0000224$. It is worth remembering that the incident spectrum not only depends on AM but also on aerosols and water vapor content at the Atmosphere. Hence, because these parameters are not taken into account, some uncertainty associated to spectral effects must remain even after applying this correction.

Finally, the irradiance signal can be corrected to 25 °C, taking into account the solar cell temperature (estimated from the ambient temperature and the global irradiance) and the corresponding coefficient provided by the cell manufacturer. That leads to a final corrected calibration value of 90.796 mV/(kW/m²). The corresponding uncertainty is 0.988% for $k=1$ (Type A: 0.67%; Type B: 0.730%, where 0.107% comes from the reference sensors, 0.174% from the angle correction, 0.674% from the temperature correction and 0.180% from the AM correction). Interestingly, the final dispersion of the corrected data (Type A: 0.67%) is lower than the dispersion of the data without making any correction (Type A: 0.86%), which is a symptom of the soundness of the corrections.

The CIEMAT calibration has carried out on a day with clear sky conditions. The solar cell concerned and a secondary pyranometer were exposed to the sun at 40.4° latitude on a tilted and south-oriented surface. The calibration was carried out for an irradiance of more than 600 W/m². The uncertainty reported by the CIEMAT is 1% ($k=1$). Again, corrections can be made for the angle of acceptance (we have assumed a diffuse/global ratio equal to 10%), for the spectrum and the solar cell temperature. The final corrected calibration value is 90.354 mV/(kW/m²) with an uncertainty of 1.459% (Type A: 0.783%; Type B: 1.23% where 1% comes from the CIEMAT calibration, 0.174% from the angle correction, 0.674% from the temperature correction and 0.180% from the AM correction).

The internal calibration was also carried out on a day with clear sky conditions. The cell concerned and a secondary reference cell calibrated by the NREL with an uncertainty of 0.7 % ($k=1$) are exposed to the sun, and the calibration is made for $G \geq 800$ W/m². The NREL calibration is made at a solar simulator against a primary reference c-Si. Only temperature corrections are required and standard deviation goes from 1.05% to 1.445%.

Interestingly, the primary devices at the origin of the corresponding traceability chains are different, so that we can consider these calibrations as mutually independent and derive the weighted average and their expanded uncertainty, following^{[63], [68], [69]} as:

$$\bar{x} = \frac{\sum_{i=1}^n w_i x_i}{\sum_{i=1}^n w_i} = \frac{\sum_{i=1}^n \frac{x_i}{\sigma_i^2}}{\sum_{i=1}^n \frac{1}{\sigma_i^2}} \quad (6)$$

with $w_i = \frac{1}{\sigma_i^2}$, and $\sigma_i = \frac{UC95\% (k=2)}{2}$, where $\bar{x}$ is the weighted mean, w_i is the weight assigned to each calibration and σ_i corresponds to the standard deviation ° of each calibration. The weighted means standard deviation can be calculated by:

° UC95% ($k=2$) is the expanded uncertainty related to a confidence interval of 95% ($k=2$).

$$\sigma_{\bar{x}} = \frac{\sqrt{\sum_{i=1}^n w_i^2 \sigma_i^2}}{\sum_{i=1}^n w_i} = \frac{1}{\sqrt{\sum_{i=1}^n \frac{1}{\sigma_i^2}}} \quad (7)$$

This equation lead to assign a final calibration value of 90.899 mV/(kW/m²) with a standard deviation of 0.67%. Figure 17 shows the different calibration values:

Figure 17. Calibration values of the reference cell from different laboratories once they have been corrected by thermal, angular and AM effects (see Table 6). The red horizontal lines correspond to the calibration values, the rectangles limit $\pm\sigma$ intervals and the vertical lines limit $\pm 2\sigma$ intervals. The last one, in black and with the horizontal line in white, corresponds to weighted average.

It could be said that, as the initial calibration value provided by the reference cell manufacturer is very close to the final value assigned after comparing different calibrations, this rather painstaking comparison exercise is superfluous. However, we must warn against this idea. In fact, we have acquired two reference cells from the same manufacturer and their corresponding G_{ef} measurements, when exposed together to the sun and using their initial calibration values, differ consistently by about 3.4%. This difference is consistent with the expanded uncertainty claimed by the manufacturer (4% for $k=2$), but not with the uncertainty reached after the comparison performed here. It is also worth mentioning that the final uncertainty (0.67%) is lower than the lowest reported for calibration at pulsed solar simulators^[70].

3.3 PV MODULE CHARACTERIZATION IN THE SOLAR BOX

3.3.1 RATED POWER

Figure 18 shows a representative I - V curve obtained at the beginning of the measuring process with the Solar Box and close to STC. The PV module is an *Atersa A245P*, with 60 polycrystalline-Si cells and a nominal power of 245 W_p, and it has been stabilized after 60 kWh/m² of exposure to the sun. The particular measurement conditions are $G_{\text{ef}} = 1003 \text{ W/m}^2$ and $T_C = 24.4 \text{ }^\circ\text{C}$.

Figure 18. Current versus voltage, I - V , curve measured outdoors almost at STC with the Solar Box.

Table 7 details the values of the characteristic parameters for both the measured and the corrected STC I - V curves. The low impact of this correction, about 0.6% in P_{MPP}^* , is noticeable. Later we will see that the finally assigned P_{MPP}^* value, resulting from several measurements performed along a year, is 237.4 W (section 3.3.4.1). The slight difference between individual and average results (237.7 W and 237.4 W respectively, 0.1%) can be understood as an indication of low uncertainty.

Electrical parameters	I_{SC} (A)	V_{OC} (V)	I_{MPP} (A)	V_{MPP} (V)	P_{MPP} (W)	FF
Measured	8.61	37.66	8.05	29.66	239.0	0.737
Extrapolated to STC	8.59	37.58	8.04	29.56	237.6	0.736
Difference (%)	0.23	-0.21	0.12	0.34	0.58	0.14

Table 7. Values of the measured and extrapolated to STC characteristics parameters.

3.3.2 TEMPERATURE COEFFICIENTS

Initially the Solar Box was designed to characterize the electrical parameters of a PV module at STC. But, taking advantage of the PV module's natural heating process, a more detailed characterization can be achieved if more I - V curves are obtained once the front cover of the Solar Box has been removed and the PV module at STC has been measured. Figure 19 shows the evolution of the characteristics of the PV module versus the temperature for the same module as section 3.3.1. Their slope determines the value of the corresponding temperature coefficients:

$$\alpha = \frac{1}{I_{SC}^*} \frac{dI_{SC}}{dT_C}; \quad \beta = \frac{1}{V_{OC}^*} \frac{dV_{OC}}{dT_C}; \quad \gamma = \frac{1}{P_{MPP}^*} \frac{dP_{MPP}}{dT_C} \quad (8)$$

Furthermore, the temperature coefficient of the FF (δ) can be obtained by:

$$\delta = \frac{1}{FF^*} \frac{dFF}{dT_C} = \gamma - (\alpha + \beta) \quad (9)$$

For a T_C ranging from 22 to 59 °C, the results of the coefficients are: $\alpha = 0.053$ %/°C, $\beta = -0.31$ %/°C, $\gamma = -0.43$ %/°C and $\delta = -0.17$ %/°C. Figure 20 shows the evolution time of T_C and the corresponding non-uniformity throughout the heating process. It is worth mentioning that we have performed some measurements by taking the additional precaution of covering the backsheet of the module with a thermally-insulating foil. As expected, the final stabilized module temperature has increased from about 60 to 70 °C^[54]. However, we did not observe significant differences in the

resulting values of the temperature coefficients. Hence, we decided to disregard this precaution in our standard procedure.

Figure 19. PV module characteristics versus module temperature, throughout the measuring process.

Figure 20. (a) Evolution of the temperature of the module (T_c) and evolution of the maximum temperature difference among the 9 PT1000 throughout the measurement process. (b) Temperatures of the 9 PT1000 at the start of the process. (c) Temperatures of the 9 PT1000 at the end of the process.

3.3.3 IRRADIANCE COEFFICIENTS

A critical review^[71] of different available models for PV efficiency led us to conclude that only three independent parameters, one for temperature and two for irradiance, suffice to describe the performance of PV modules accurately in relative terms to STC. The oldest model complying with this idea was proposed fourteen years ago^[72] and is given by:

$$\eta' = (1 + \gamma T')(a_1 + a_2 G' + a_3 \ln G') \quad (10)$$

where

$$\eta' = \frac{\eta}{\eta^*}; \quad G' = \frac{G}{G^*} \text{ and } T' = T_c - T_c^* \quad (11)$$

where η is the efficiency of the PV module and a_1 , a_2 and a_3 are empirically adjusted parameters. The particularization of this equation for STC leads to the condition:

$$a_1 + a_2 = 1 \quad (12)$$

Consequently, equation (10) can be rewritten as:

$$\eta' = (1 + \gamma T')(a_1 + (1 - a_1)G' + a_3 \ln G') \quad (13)$$

This requires only three parameters, one for temperature and two for irradiance. As the PV module concerned has been characterized first in terms of I_{SC}^* , V_{OC}^* , P_{MPP}^* , α , β and γ , we can derive the two irradiance parameters from just two I - V curves obtained at two irradiances other than G^* . This time we can manage without the Solar Box. We simply obtain 4 I - V curves at irradiances close to 200, 400, 600 and 800 W/m²,

irrespective of the temperature of the module^f. Four curves instead of only two are enough for a better adjustment. Each curve is treated as follows:

First, G_{ef} and T_C are derived from I_{SC} and V_{OC} by:

$$G_{ef} = \frac{I_{SC}}{I_{SC}^*} G^* [1 + \alpha(T_C - T_C^*)]^{-1} \quad (14)$$

$$V_{OC}^C = V_{OC} + N_S \frac{mk}{q} (T_C + T_0) \cdot \ln \frac{G_{ef}}{G^*} \quad (15)$$

$$T_C = T_C^* + \left(\frac{V_{OC}^C}{V_{OC}^*} - 1 \right) / \beta \quad (16)$$

where N_S is the number of solar cells associated in series, k is the Boltzmann constant ($1.38 \times 10^{-23} \text{ J} \cdot \text{K}^{-1}$), q is the elementary charge ($1.6 \times 10^{-19} \text{ C}$), m is the ideality factor of the diode ($m=1.3$ is a reasonable choice for c-Si), T_C is expressed in °C, T_0 is the absolute temperature at 0 °C (273.15 K) and V_{OC}^C can be understood as the open circuit voltage corrected in irradiance. Note that equations (14) to (16) form a non-linear equation system with no analytical solution. However, it is easily solved numerically through an iterative process starting with $T_C = T_C^*$. Typically, two iterations lead to errors of well below 1 %. It must be stressed that effective incident irradiance is directly determined from the I_{SC} itself of the PV module tested, once the corresponding STC value has been measured in a previous step. It has been referred that this leads to less uncertainty than using a dedicated irradiance sensor^[73] (this is also our experience).

Second, the relative efficiency corrected to T_C^* , η'_G , is calculated as:

^f Note that in equation (15) the correction term related to a cell temperature different than 25 °C, $+\beta \cdot N_S(T_C - T_C^*)$, has been neglected.

$$\eta'_G = \frac{P_{MPP}}{P_{MPP}^*} \frac{1}{1 + \gamma T'} \frac{1}{G'} \quad (17)$$

and the values of a_1 , a_2 and a_3 are determined from the best fit of the second term in equation (10) to the four η'_G resulting values. Finally, $\eta'_{0.6}$ and $\eta'_{0.2}$ (the relative efficiencies at $G = 600 \text{ W/m}^2$ and $G = 200 \text{ W/m}^2$, respectively) are calculated and given as reference values, which allows the parameters of any PV efficiency versus irradiance model to be adjusted (Table 8 and Figure 21 presents the measurements performed on the same PV module than in sections 3.3.1 and 3.3.2).

Measurements			G_{ef} (W/m ²)	T_{C} (°C)	η'_{G}
I_{SC} (A)	V_{OC} (V)	P_{MPP} (W)			
8.61	37.53	237.4	1000	25	1
1.80	34.15	45.0	190	12.0	0.946
3.52	35.47	90.7	370	15.6	0.994
5.26	36.25	140.6	566	19.5	1.022
6.99	36.77	189.1	780	22.7	1.012
Model parameter					
a ₁ = 1.22		a ₂ = -0.22		a ₃ = 0.14	
Reference values					
η _{0.2} ' = 0.95			η _{0.6} ' = 1		

Table 8. Measurements at 4 different operating conditions and derived efficiency versus irradiance model parameters.

Figure 21. Relative efficiency, η'_G versus irradiance, G , observed values (corrected to 25 °C) and fitted curve.

3.3.4 UNCERTAINTY ON THE PV MODULE CHARACTERISTICS USING THE “SOLAR BOX”

Table 9 presents the uncertainty components identified in this work. Following the analysis and terminology contained in the Guide to the Expression of Uncertainty in Measurements^[74], it is indicated whether they are considered as Type A (whose uncertainty is estimated as the standard deviation of a series of repeated determinations) or Type B (whose uncertainty is calculated from the instrument’s accuracy and calibration characteristics). Table 9 also indicates the corresponding affected parameter.

Uncertainty	Component	Type	P_{MPP}^*	I_{SC}^*	V_{OC}^*	Temp. Coeff.	Irrad. Coeff.
Irradiance	Reference cell calibration	B	X	X			
	Spectral mismatch	A	X	X			
	Misalignment	A	X	X			
	Data Acquisition System	B	X	X			
Temperature	PT1000	B	X				
	Non-uniformity	B	X		X	X	X
	Backskin-to-cell drop	B				X	
	Data Acquisition System	B	X	X	X	X	
Electrical	Data Acquisition System	B	X	X	X	X	X
Corrections	I - V curve to STC	A	X	X	X		
	T_C from V_{OC}	B					X
	$P_{MPP}(T_C)$ to $P_{MPP}(T_C^*)$	A					X

Table 9. Uncertainty components identified in this work. It is indicated whether they are considered as Type A or Type B, as are the affected parameter results.

3.3.4.1 TYPE A UNCERTAINTIES

In order to quantify Type A uncertainties, we have periodically characterized a single PV module over a full year and analysed the repeatability of results. The PV module model is the same *Atersa A245P* than in section 3.3.1. Over 2014, 15 measurements were taken (approximately once per month) and the PV module was kept in the dark between them. Figure 22a shows the time evolution of the measured P_{MPP}^* and Figure 22b, the distribution of residuals with respect to the average value. This can be represented by a mean value, $\overline{P_{MPP}^*} = 237.4$ W, and a standard deviation, $u_A^{P_{MPP}^*} =$

0.31%. This deviation is taken as a proper estimation of the Type A standard uncertainty ($k=1$). Table 10 extends the exercise to the remaining characteristic parameters. The figures corresponding to the other parameters are reported in APPENDIX B.1.

Figure 22. (a) P_{MPP}^* of a PV module measured 15 times over a whole year inside the Solar Box. The continuous line represents the mean value of all the measurements and the dotted lines represent a deviation of 0.7% which includes all the measurements. (b) Distribution of residuals with respect to the average value.

P_{MPP}^* (W)	I_{MPP}^* (A)	V_{MPP}^* (V)	I_{SC}^* (A)	V_{OC}^* (V)	FF^*	α (%/°C)	β (%/°C)	γ (%/°C)	$\eta'_{0.6}$	$\eta'_{0.2}$
237.4	8.06	29.47	8.61	37.53	0.734	0.06	-0.32	-0.43	1	0.94
$u_A^{P_{MPP}}$ (%)	$u_A^{I_{MPP}}$ (%)	$u_A^{V_{MPP}}$ (%)	$u_A^{I_{SC}}$ (%)	$u_A^{V_{OC}}$ (%)	u_A^{FF} (%)	u_A^α (%/°C)	u_A^β (%/°C)	u_A^γ (%/°C)	$u_A^{\eta'_{0.6}}$ (%)	$u_A^{\eta'_{0.2}}$ (%)
0.31	0.40	0.21	0.43	0.16	0.24	0.008 (13.33%)	0.010 (3.13%)	0.019 (4.41%)	0.50	0.68

Table 10. Average and standard deviation (in %) of the characteristic parameters measured on a same PV module 15 times over a year.

3.3.4.2 TYPE B UNCERTAINTIES

Table 11 presents the input information (instruments manufacturer specifications, updated calibration certificates, experimental requirements, assumptions, etc.) and the corresponding derived standard uncertainties for Type B components. The shape of the density function for each uncertainty component is generally assumed to be rectangular, so the corresponding standard uncertainty is given by:

$$u_B = \frac{a}{\sqrt{3}} \quad (18)$$

where a is the interval within which the expected value of the measurement lies. In turns, it is the $\pm$ accuracy typically specified by the instrument manufacturer or the requirement imposed on a given experiment. For example, the PT1000 are specified (manufacturer data) with a tolerance of ± 0.415 °C. This result translates into a standard uncertainty, $u_B^{PT1000} = \pm 0.240$ °C. On similar lines, imposing 3 °C as the maximum difference between the readings of the 9 PT1000 glued to the back of the PV module is interpreted as a ± 1.5 °C interval and leads to $u_B^{\Delta T3} = \pm 0.866$ °C. The drop in temperature between the cells and the PV module backskin is considered to be 3 °C with a range of ± 1 °C^{[52], [53]}. Data Acquisition System (D.A.S.) is made up of an oscilloscope and a datalogger, which are of 12 and 20 bit digitization respectively. Measurement ranges are selected in order to obtain signal values larger than half of the full scale.

Component, i	Input information	Standard uncertainty
Reference cell calibration	Crossing different calibrations (section 3.2). Normal distribution	$u_B^{RCC} = 0.67\%$
PT1000	Accuracy ^g : ± 0.415 °C	$u_B^{PT1000,STC} = 0.24$ °C
Non-uniform temperature	≤ 3 °C at STC ≤ 7 °C at other than STC	$u_B^{\Delta T3} = 0.866$ °C $u_B^{\Delta T7} = 2.021$ °C
Backskin-to-cell drop temperature	≤ 3 °C Range: ± 1 °C	$u_B^{BTC} = 0.577$ °C
D.A.S - Oscilloscope	Accuracy: $\pm 0.2\%$ Resolution: 12 bits digitization	$u_B^{Osc} \leq 0.116\%$ (Accuracy: $\leq 0.116\%$) (Resolution: $\leq 0.011\%$)
D.A.S - Datalogger	Accuracy (V_{DC}): 0.005% of reading + 0.004% of range Accuracy (Temp.): 0.06 °C Resolution: 20 bits digitization	$u_B^{Dat,Gef} \leq 0.005\%$ (Accuracy: $\leq 0.005\%$) (Resolution: $\leq 0.00003\%$) $u_B^{Dat,Tc} \leq 0.035$ °C (Accuracy: ≤ 0.035 °C) (Resolution: ≤ 0.0001 °C)
Calibrated resistor	Accuracy: $\pm 0.5\%$	$u_B^{Res} = 0.289\%$

Table 11. Input information of the instruments and components used in the measurements and the corresponding derived standard uncertainties for the Type B components.

^g This value corresponds to STC. At other conditions: $\pm(0.3+0.005|T|)$.

All these uncertainty components are mutually independent. Hence, the resulting Type B uncertainties on G_{ef} and T_C are estimated as^h:

$$u_B^{G_{ef}} = \sqrt{(u_B^{RCC})^2 + (u_B^{Dat,G_{ef}})^2} = \sqrt{(0.67)^2 + (0.005)^2} = 0.67\% \quad (19)$$

$$\begin{aligned} u_B^{T_C(STC)} &= \sqrt{(u_B^{PT1000,STC})^2 + (u_B^{\Delta T3})^2 + (u_B^{BTC})^2 + (u_B^{Dat,T_C})^2} \\ &= \sqrt{(0.24)^2 + (0.866)^2 + (0.577)^2 + (0.035)^2} \\ &= 1.07 \text{ }^\circ\text{C} \text{ (4.3\%)} \end{aligned} \quad (20)$$

$$\begin{aligned} u_B^{T_C(50 \text{ }^\circ\text{C})} &= \sqrt{(u_B^{PT1000,50^\circ\text{C}})^2 + (u_B^{\Delta T7})^2 + (u_B^{BTC})^2 + (u_B^{Dat,T_C})^2} \\ &= \sqrt{(0.32)^2 + (2.021)^2 + (0.577)^2 + (0.035)^2} \\ &= 2.13 \text{ }^\circ\text{C} \text{ (4.3\%)} \end{aligned} \quad (21)$$

Table 12 shows the Type B uncertainty on the directly measured electrical parameters (I_{SC} , V_{OC} and P_{MPP}) in %, as well as the uncertainty on α , β and γ in %/ $^\circ\text{C}$. The subscript “m” indicates directly measured values. Uncertainties on I_{MPP} and V_{MPP} , which are the inputs for P_{MPP} uncertainty calculation, are considered to be the same as those corresponding to I_{SC} and V_{OC} , respectively. As a matter of example, the uncertainty on $I_{SC,m}$ and $P_{MPP,m}$ are given by:

$$u_B^{I_{SC,m}} = \sqrt{(u_B^{Osc})^2 + (u_B^{Res})^2} = \sqrt{(0.116)^2 + (0.289)^2} = 0.311\% \quad (22)$$

^h The detailed calculation of uncertainty for all the parameters can be found in APPENDIX A.2.

$$\begin{aligned}
u_B^{P_{MPP,m}} &= \sqrt{(u_B^{I_{SC,m}})^2 + (u_B^{V_{OC,m}})^2} = \sqrt{(0.311)^2 + (0.116)^2} \\
&= 0.332\%
\end{aligned} \tag{23}$$

	$I_{SC,m}$ (%)	$V_{OC,m}$ (%)	$P_{MPP,m}$ (%)	$\alpha_{I_{SC}}$ (%/°C)	$\beta_{V_{OC}}$ (%/°C)	$\gamma_{P_{MPP}}$ (%/°C)
Temperature				0.0045	0.026	0.036
D.A.S. - Oscilloscope	0.116	0.116				
Calib. Resistor	0.289					
$I_{measured}$			0.311	0.0124		
$V_{measured}$			0.116		0.0045	
$P_{measured}$						0.013
u_B (%)	0.311	0.116	0.332	0.013 (21.66%)	0.026 (8.13%)	0.038 (8.84%)

Table 12. Standard Type B uncertainties on the measured current, voltage and power, and on the temperature coefficients ($k=1$). Each one of the values of the components which contribute to the final value of uncertainty is also included.

Uncertainties on the temperature coefficients are estimated using the law of propagation of uncertainty: the combined standard uncertainty is the square root of the sum of the sensitivity coefficients (partial derivate of the equation with respect to the input parameter to be analyzed) squared, multiplied by its squared uncertainty.

$$u_c(y) = \sqrt{\sum_{i=1}^N \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i)} \tag{24}$$

For example, in accordance with equation (8), the uncertainty sources for α are $I_{SC,m}$ and T_C . The corresponding calculations are (based on values from Figure 19):

$$\frac{\partial \alpha}{\partial I_{SC}} = \frac{1}{I_{SC}^*} \cdot \frac{1}{T_C - T_C^*} \approx \frac{1}{25} = 0.04 \frac{1}{^\circ\text{C}} \tag{25}$$

$$\frac{\partial \alpha}{\partial T_c} = \frac{1}{I_{sc}^*} \cdot \frac{I_{sc} - I_{sc}^*}{(T_c - T_c^*)^2} = \frac{1}{8.61} \cdot \frac{0.115}{(25)^2} \cdot 100 = 2.14 \cdot 10^{-3} \frac{\%}{^\circ\text{C}^2} \quad (26)$$

$$\begin{aligned} u_B^\alpha &= \sqrt{\left(\frac{\partial \alpha}{\partial I_{sc}} \cdot u_B^{I_{sc,m}}\right)^2 + \left(\frac{\partial \alpha}{\partial T_c} \cdot u_B^{T_c(50^\circ\text{C})}\right)^2} = \\ &= \sqrt{(0.04 \cdot 0.311)^2 + (2.14 \cdot 10^{-3} \cdot 2.13)^2} = \\ &= \sqrt{(0.0124)^2 + (0.0045)^2} = 0.013 \frac{\%}{^\circ\text{C}} \quad (21.66\%) \end{aligned} \quad (27)$$

Table 13 shows the uncertainty on the STC characteristics. Again, the propagation law is applied to consider the required corrections. For example, I_{sc}^* is given by:

$$I_{sc}^* = I_{sc,m} \cdot \frac{G^*}{G_{ef}} \cdot \frac{1}{1 + \alpha(T_c - T_c^*)} \quad (28)$$

So G , T_c , $I_{sc,m}$ and α are the uncertainty sources. The corresponding calculations are:

$$\frac{\partial I_{sc}^*}{\partial G_{ef}} = \frac{I_{sc,m}}{1 + \alpha(T_c - T_c^*)} \cdot \frac{-1}{G_{ef}} \approx \frac{1}{1 + \frac{0.06}{100}(1.07)} = 0.999 \quad (29)$$

$$\frac{\partial I_{sc}^*}{\partial T_c} = I_{sc,m} \frac{-\alpha}{[1 + \alpha(T_c - T_c^*)]^2} \approx \frac{-0.06}{\left[1 + \frac{0.06}{100}(1.07)\right]^2} = 0.06\% \quad (30)$$

$$\frac{\partial I_{sc}^*}{\partial I_{sc,m}} = \frac{1}{1 + \alpha(T_c - T_c^*)} = \frac{1}{1 + \frac{0.06}{100}(1.07)} = 0.999 \quad (31)$$

$$\frac{\partial I_{SC}^*}{\partial \alpha} = I_{SC,m} \frac{-(T_C - T_C^*)}{[1 + \alpha(T_C - T_C^*)]^2} \approx \frac{-(1.07)}{\left[1 + \frac{0.06}{100}(1.07)\right]^2} = 1.069^\circ\text{C} \quad (32)$$

$$\begin{aligned} u_B^{I_{SC}^*} &= \\ &= \sqrt{\left(\frac{\partial I_{SC}^*}{\partial G_{ef}} \cdot u_B^{G_{ef}}\right)^2 + \left(\frac{\partial I_{SC}^*}{\partial T_C} \cdot u_B^{T_C(STC)}\right)^2 + \left(\frac{\partial I_{SC}^*}{\partial I_{SC,m}} \cdot u_B^{I_{SC,m}}\right)^2 + \left(\frac{\partial I_{SC}^*}{\partial \alpha} \cdot u_B^\alpha\right)^2} \\ &= \sqrt{(0.999 \cdot 0.67)^2 + (0.06 \cdot 1.07)^2 + (0.999 \cdot 0.311)^2 + (1.069 \cdot 0.013)^2} \quad (33) \\ &= \sqrt{(0.67)^2 + (0.064)^2 + (0.311)^2 + (0.014)^2} = 0.742\% \end{aligned}$$

	I_{SC}^* (%)	V_{OC}^* (%)	P_{MPP}^* (%)	FF^* (%)	η^* (%)
Irradiance	0.67		0.67		0.67
Temperature	0.064	0.345	0.464	0.183	0.464
I_{measured}	0.311				
V_{measured}		0.116			
P_{measured}			0.334		
FF_{measured}				0.334	
P_{MPP}^*					0.888
$\alpha_{I_{SC}}$	0.014				
$\beta_{V_{OC}}$		0.028			
$\gamma_{P_{MPP}}$			0.041		0.041
δ_{FF}				0.001	
u_B (%)	0.742	0.365	0.882	0.381	1.206

Table 13. Standard Type B uncertainties on the extrapolated current, voltage, power, FF and efficiency ($k=1$). Each one of the values of the components which contribute to the final value of uncertainty (sensitivity coefficient multiplied by the standard uncertainty) is also included.

As expected, the uncertainty in the determination of the current and voltage at STC are basically related to the measurement of the irradiance and cell temperature, respectively. Thus, in the uncertainty on the maximum power, the uncertainty associated with the measurement of irradiance prevails, with an also important contribution from the measurement of the cell temperature.

3.3.4.3 COMBINED AND EXPANDED UNCERTAINTIES

Again, the uncertainty components are considered as mutually independent. Hence, the combined uncertainty for a particular result is given by:

$$u_c = \sqrt{u_A^2 + \sum_i (u_B^i)^2} \quad (34)$$

where “i” stands for all the Type B components. Table 14 shows the combined standard uncertainty on the STC parameters and on the temperature coefficients.

$u_c^{P_{MPP}}_{\text{(\%)}}$	$u_c^{I_{sc}}_{\text{(\%)}}$	$u_c^{V_{oc}}_{\text{(\%)}}$	$u_c^{FF^*}_{\text{(\%)}}$	$u_c^{\alpha}_{\text{(\%/°C)}}$	$u_c^{\beta}_{\text{(\%/°C)}}$	$u_c^{\gamma}_{\text{(\%/°C)}}$	$u_c^{\eta'}_{\text{(\%)}}$
0.935	0.858	0.399	0.45	0.015 (25.43%)	0.028 (8.71%)	0.042 (9.88%)	1.21

Table 14. Combined standard uncertainty on the STC parameters and on the temperature coefficients.

Figure 23 and Figure 24 show graphically the impact of Type A and Type B (irradiance; temperature; measured I , V , P and FF ; and the temperature and irradiance coefficients) uncertainties on the combined uncertainty for each electrical parameter and irradiance and temperature coefficients. As mentioned above, it can be observed that the uncertainties coming from the measurement of G_{ef} and T_C are the ones which have more contribution to the final uncertainty.

Figure 23. Impact of Type A and Type B uncertainties (irradiance, temperature, electrical measured parameters and temperature coefficients) on the combined uncertainty of the electrical parameters extrapolated to STC.

Figure 24. Impact of Type A and Type B uncertainties (irradiance, temperature, electrical measured parameters and temperature coefficients) on the combined uncertainty of the irradiance and temperature coefficients.

To obtain the expanded uncertainty, U , it is enough to multiply the values of Table 14 by the corresponding coverage factor, k (the values in the table have a coverage factor of $k=1$). A typical value for k is 2, which is associated with a confidence interval of 95% when corresponds to a Gaussian distribution^[58] ($k=3$ for 99%).

3.3.4.4 INTERCOMPARISON

We have compared the results of our outdoor measurements for three different PV modules with the results from a high quality pulsed solar simulator available at CIEMAT (Pasan 3b with class AAA in accordance with IEC-60904-9 with a flash duration of 10 ms), respectively. Table 15 shows the results. The maximum power is within an interval of 0.65% (from -0.11% to 0.54%), which is of the order of the differences observed at worldwide intercomparison between reference laboratories ($\pm 1.3\%$ for crystalline silicon modules^[69]).

It is worth mentioning that we also had a medium quality pulsed solar simulator (Berger PSS 8 with class A, flash duration of 10 ms). The irradiance level is adjusted with the same reference cell we used for outdoor measurements. Table 16 compares the measurements from both solar simulators. Interestingly, the differences are larger than those corresponding to the outdoor measurements.

	P_{MPP}^* (W)	I_{MPP}^* (A)	V_{MPP}^* (V)	I_{SC}^* (A)	V_{OC}^* (V)	FF^*
<i>M1: Atersa A245P, 60 polycrystalline-Si cells, $P_{NOM}^* = 245 W_p$</i>						
Flash CIEMAT	239.7	7.96	30.12	8.56	37.46	0.748
Outdoor IES	241.0	8.08	29.83	8.60	37.60	0.750
Difference (%)	0.54	1.51	-0.96	0.47	0.37	0.27
<i>M2: Solon P215, 60 polycrystalline-Si cells, $P_{NOM}^* = 215 W_p$</i>						
Flash CIEMAT	209.2	7.40	28.27	7.99	36.16	0.724
Outdoor IES	209.0	7.44	28.09	8.03	36.29	0.717
Difference (%)	-0.11	0.50	-0.63	0.46	0.35	-0.97
<i>M3: Yingli YL230, 60 monocrystalline-Si cells, $P_{NOM}^* = 230 W_p$</i>						
Flash CIEMAT	235.5	7.98	29.49	8.44	36.72	0.760
Outdoor IES	236.6	8.04	29.43	8.51	36.80	0.756
Difference (%)	0.45	0.72	-0.20	0.80	0.23	-0.56

Table 15. Difference in the results of the measurements with the solar simulators from CIEMAT and measurements taken at real sun with the Solar Box.

	P_{MPP}^* (W)	I_{MPP}^* (A)	V_{MPP}^* (V)	I_{SC}^* (A)	V_{OC}^* (V)	FF^*
<i>M1: Atersa A245P, 60 polycrystalline-Si cells, $P_{NOM}^* = 245 W_p$</i>						
Flash CIEMAT	239.7	7.96	30.12	8.56	37.46	0.748
Flash IES	244.3	8.03	30.43	8.59	37.45	0.760
Difference (%)	1.92	0.88	1.03	0.35	-0.03	1.58
<i>M2: Solon P215, 60 polycrystalline-Si cells, $P_{NOM}^* = 215 W_p$</i>						
Flash CIEMAT	209.2	7.40	28.27	7.99	36.16	0.724
Flash IES	212.5	7.46	28.48	7.96	36.11	0.739
Difference (%)	1.57	0.81	0.74	-0.38	-0.14	2.06
<i>M3: Yingli YL230, 60 monocrystalline-Si cells, $P_{NOM}^* = 230 W_p$</i>						
Flash CIEMAT	235.5	7.98	29.49	8.44	36.72	0.760
Flash IES	240.8	7.98	30.17	8.52	36.70	0.770
Difference (%)	2.23	0.00	2.31	0.95	-0.05	1.30

Table 16. Difference in the results of the measurements with the solar simulators from CIEMAT and GS-IES-UPM.

In the previous tables can be observed that depending on the quality and calibration of the solar simulator used to characterize a PV module, the obtained results can be considered (or not) representative of its behavior in the field^[75]. In addition, outdoor measurements obtained using the Solar Box and the twin capacitive load, and with the appropriate care, lead to results comparable to those obtained with the best simulators available in the market. So, a field characterization measurement can be considered also very accurate.

3.4 DEALING WITH REFERENCE PV MODULES

3.4.1 CONSTITUTION AND CALIBRATION

A PV reference module is a module of the same type as the one used in the device under test (another PV module or a PV array). Because both, the reference and the tested device, have the same spectral, angular and thermal responses, using reference modules as G_{ef} and T_C sensors led to the lowest possible uncertainty on the performance characteristic of the tested device. Equations relating G_{ef} and T_C with I_{SC} and V_{OC} have been described above ((14) and (16)). I_{SC} is usually obtained from the voltage drop across a calibrated resistor with very low temperature coefficient (typically a manganine resistor, which has a thermal coefficient of electrical resistance of $10^{-5} ^\circ C^{-1}$). In order to assure the linearity between this signal and G_{ef} , the resistance must be

relative low. According with IEC-60904-2ⁱ, this resistance must assure that the voltage drop is lower than 3% of the V_{OC}^* value. Meanwhile, V_{OC} is measured directly or through a voltage divider for adapting the signal to the D.A.S. requirements. In practice, one can use either two different modules, for I_{SC} and V_{OC} respectively, or only one module^[37]. In this case, an intermediate point is accessed in the module connection box, thus dividing the module into two different sections, one for I_{SC} and the other for V_{OC} (Figure 25).

Whichever the case, the reference modules can be calibrated in I_{SC}^* , V_{OC}^* , α and β , following the same procedure described in section 2.3. This time only I_{SC} and V_{OC} , instead of full I - V curves, are needed. Then, the resistor and the voltage divider are added and the relations between the corresponding signals and G_{ef} and T_C are straightforward derived using the characteristics of these devices. However, one can proceed better doing just the opposite: first, installing the resistor and the voltage divider and, then, directly calibrating the corresponding signals. That led to lower uncertainty on the calibration values, because the Type B uncertainty contributions due to the resistor and to the voltage divider are this way avoided.

Figure 25. (a) Scheme of a modified PV module to measure the operating conditions, G_{ef} and T_C . (b) Junction box added to the module that contains a high-precision resistor and connections to obtain the G_{ef} and T_C signals in mV and V, respectively.

ⁱ IEC-60904-2: Photovoltaic devices. Part 2: Requirements for reference solar devices. Section 3.3: Built-in shunt resistors.

3.4.2 UNCERTAINTY ON G_{EF} AND T_{C} MEASUREMENTS

As a representative case, we have prepared 20 PV modules of the same model (Yingli YL250-29b 250 W_p) to be used as G_{ef} and T_{C} sensors in large PV plants. All of them were previously submitted to an exposure to the sun of about 60 kWh/m² and revised using electroluminescence, in order to assure that they are well stabilized and fully free of internal defects. Half of them are going to be used as G_{ef} sensors. For that, they were shunted by means of calibrated resistors (Class 0.5, high thermal stability). Corresponding irradiance signals are the drop in voltage at these resistors. The other half is going to be used as T_{C} sensors, which corresponding signals are the open circuit voltages.

Next, we installed the 20 PV modules on the same surface (30° tilted, South oriented) and we compared their G_{ef} and T_{C} measurements over several days (May 19th and 20th, 2016 for G_{ef} and June 2nd and 5th, 2016 for T_{C}). The corresponding differences have been the basis for estimating the uncertainty.

3.4.2.1 UNCERTAINTY ON IRRADIANCE

Figure 26 shows the average of the 10 G_{ef} individual measurements and the corresponding difference between each individual measurement and this average. Differences are within $\pm 1\%$, which is consistent with the uncertainties on the characterization of the I_{SC}^* signal described above (1% is close to one standard deviation). As all of the PV modules receive the same irradiance, the uncertainty on the average value is lower than for the measurement of a single PV module. In particular, Type A uncertainty is divided by $\sqrt{N}$, being N the number of PV modules. This allows the calibration to be refined in such a way that all of the modules give measurements as close as possible to the average value. Figure 27 shows the evolution of the difference in the irradiance measured by two of these PV modules - after refining the calibration - versus the angle of incidence of the direct irradiance component, θ_{S} . The key point is to realize that the difference increases sharply for $\theta_{\text{S}} > 50^\circ$, which can be explained by slight differences in angle of incidence, due to the frame not being perfectly flat all

over. The resulting combined uncertainty is 0.93% for $\theta_s \leq 50^\circ$ (Type A: 0.43%, Type B: 0.82%) and 1.40% for $\theta_s > 50^\circ$ (Type A: 0.43%, Type B: 1.33%).

Figure 26. Effective irradiance, G_{ef} , obtained by the average of the 10 PV modules and differences between this average and each module for irradiances above 600 W/m² (for clarity of presentation, the differences are shown for only three modules). Measurements have been recorded on May 19th, 2016.

Figure 27. Difference in the effective irradiance measured by two reference modules on a clear day (May 19th) versus the angle of incidence.

3.4.2.2 UNCERTAINTY ON PV MODULE TEMPERATURE

Figure 28 shows the 10 values of T_C measured with clear sky (June 2nd, 2016) with a cell temperature close to 65 °C at noon. The maximum difference between PV modules during the two days of T_C calibration (June 2nd and 5th, 2016) is ± 3.3 °C. These differences are within the expected range^[76], because the thermal dissipation process influences the module and varies from one PV module to another one, even if they are from the same manufacturer, model and type of cell. For this reason, possible calibration refinements based on compensating this difference have been disregarded. The resulting combined uncertainty is 0.399% (Type A: 0.16%, Type B: 0.365%).

Figure 28. Module temperature obtained by the average of the 10 PV modules and differences between this average and each module (for clarity of presentation, the differences are shown for only three modules). Measurements have been recorded on June 2nd, 2016.

3.5 IN-FIELD PV MODULES MEASUREMENT

The daily life of PV plant operators sometimes requires measuring PV module characteristics with reasonable accuracy. Due to practical feasibility, such measurements should preferably be done with the PV module staying on its own

operation position and at the natural module temperature. Today such measurements are usually performed by means of commercial I - V tracers which are typically delivered together with a calibrated solar cell serving as sensor of both G and T_C (required to translate the measured curves to STC). However, even assuming properly encapsulated and accurately calibrated solar cells, the module temperature is a key accuracy issue, mainly because the different thermal dissipation mechanism between PV modules and reference cells (different shapes, materials, sizes, etc.) translate into errors on the estimation of T_C when assigning to the module the same value measured at the reference cell.

3.5.1 THE PV MODULE TEMPERATURE ISSUE

One can imagine that measuring the PV module temperature directly by means of a rather accurate device, like a PT1000 ($u_B^{PT1000,STC} = 0.24$ °C), glued to the centre of the module back surface is a proper and still feasible solution. However, the T_C issue still remains due to the relatively large temperature dispersion observed along the PV module surface. As a representative example, Figure 29 presents the results of a particular experiment performed into the framework of this thesis. It has consisted in estimating the T_C of a same module by three different ways: from the V_{OC} of the module (as explained for reference modules in section 3.4.1); from a PT1000 glued to the centre of the module back surface; and from a sensor provided together with a commercial I - V tracer, in particular the TRIKA^[77]. The figure shows the observed T_C differences taking the V_{OC} method as reference. Measurements have been performed on 15 different days between September 2016 and March 2017, and have been carried out on clear days and with stable meteorological conditions. 10 measurements each day have been performed in a range of ± 30 minutes to the solar noon.

Figure 29. (a) Differences in temperature between the PT1000 (blue diamonds) and the commercial sensor (TRIKA, orange triangles) with respect to a PV reference module, and wind speed (red line). (b) Median of the difference between the sensors and the PV reference module (red horizontal line). The boxes correspond to the 95% confidence interval and the horizontal lines delimit the maximum and minimum values.

When testing PV modules on their own operation position, the dispersion of module temperature along the PV array represents an additional source of uncertainty on T_C estimation because, when using a reference module or a reference cell as T_C sensor, the distance between the module under test and the T_C sensor can be relatively large. As a representative example, Figure 30 shows the difference on T_C simultaneously observed on different modules of a same array by means of PT1000 glued in the centre of their back surfaces. This array is a 5 kW one, 11 x 3.3 m, located at the GS-IES-UPM facilities in Madrid (Campus Sur UPM), and comprising 21 PV modules. 18 PT1000 are glued at the positions signaled in Figure 30a. Figure 30b plots the maximum T_C difference among these points versus incident irradiance. The key point is that T_C differences as large as 10 °C (so, implying up to 4-5% errors in STC power determination) can be found with distances of only 11 m. Similar results have been found by researchers^j of the UPNA (Universidad Pública de Navarra) at the Amareleja PV plant, located in the South of Portugal.

^j Personal communication of García, M. and Muñoz, M. (miguel.garcia@unavarra.es).

(a)

(b)

Figure 30. Difference on T_C observed on different modules of the 5 kW array located in the GS-IES-UPM facilities. (a) Location of the PT1000, glued in the centre and the back surface of each PV module. (b) Temperature differences measured by PT1000 in the 5 kW array. Points inside the dotted grey ellipse correspond to shade situations due to a close tree and should be disregarded in the analysis.

3.5.2 A PROPOSED METHOD FOR ESTIMATING T_C

Having in mind such temperature dispersions, we have decided estimating T_C of the module under test, $T_{C,TEST}$, by combining the V_{OC} method for the reference module,

$T_{C,REF}$, with the temperature difference between the centre of the reference module, T_{REF} , and the centre of the module under test, T_{TEST} . That is:

$$\Delta T_{RT} = T_{REF} - T_{TEST} \quad (35)$$

$$T_{C,TEST} = T_{C,REF} + \Delta T_{RT} \quad (36)$$

The hope is that the V_{OC} method and the temperature sensor are able of respectively capturing the temperature dispersion along a same module and along the array. Figure 31 shows the arrangement of a particular experiment. First, 10 PV modules were previously calibrated (using the Solar Box) and installed at the GS-IES-UPM terrace with PT1000 glued at the centre of their back surfaces. Then, these modules were periodically tested by means of the twin capacitive load and taking the module number 5 as reference. The $I-V$ curve of the module under test is corrected to STC in accordance with IEC-60891 and using the G_{ef} and T_C values derived from the I_{SC} and V_{OC} of the reference module. Measurements have been performed the same days and conditions that described above.

Figure 31. Distribution of the different PV calibrated modules which have been used in the experiment carried out between September 2016 and March 2017.

Table 17 presents the mean value of the errors, understood as the difference between the P_{MPP}^* results and the corresponding calibration value. Modules 7 and 8 are of thin-film technology (CdTe) and their results have been disregarded. Likely because

the relatively short distances between the modules (less than 5 m), all the errors fall inside the expanded uncertainty range ($k=2$) estimated for the calibration of the reference module (see section 3.3.4.3). However, it is still possible to appreciate the improvement associated to correcting $T_{C,TEST}$ with ΔT_{RT} . For the case of the TRIKA I - V tracer, it can be observed that the mean difference is much greater than for the twin load, as well as its dispersion (Figure 32).

Module	Distance to the reference module (m)	Differences (%)		
		P_{MPP}^* error with $T_{C,TEST} = T_{C,REF}$	P_{MPP}^* error with $T_{C,TEST} = T_{C,REF} + \Delta T_{RT}$	P_{MPP}^* TRIKA error with $T_C = T_{C,TRIKA}$
1	4.5	-0.89	-0.72	-1.95
2	3	-0.05	0.36	-1.44
3	2	0.09	-0.14	-2.29
4	1	0.32	-0.02	-2.02
6	1	1.70	1.52	0.35
9	5	0.56	-0.21	-3.03
10	4.5	0.59	0.22	-3.13

Table 17. P_{MPP}^* error respect to the calibration value taking and not taking into account the temperature difference between the reference and the tested module using the twin capacitive load, and the error using the TRIKA I - V tracer.

Figure 32. Median of P_{MPP}^* error respect to the calibration value (red horizontal line) taking and not taking into account the temperature difference between the reference and the tested module using the twin capacitive load, and the error using the TRIKA I - V tracer. The box delimits the 95% confidence interval and the horizontal lines the maximum and minimum value for each case. Red crosses represent the points which are considered outliers.

This exciting result encouraged us to try the method in the field with larger distances between modules found in large PV arrays. That is described in the next chapter, but it can be advanced here that the result was again positive.

3.5.3 UNCERTAINTY ESTIMATIONS

The estimation of uncertainty on the STC characteristics measured with the here proposed method follows the above described path for the estimation of uncertainty on the characteristics measured with the Solar Box (section 3.3.4.2), just considering two differences. On the one hand, that now the G sensor is not the ISET reference cell but a reference module. Hence, $u_B^{G_{ef}}$ increases from 0.67% to 0.93%. On the other hand, that two new temperature uncertainty components appear respectively associated to the non-uniform distribution of temperature along a PV array (in other words, associated to assigning the T_C value measured in the reference module to another module in a different position) and to the sensors used for measuring ΔT_{RT} . Figure 33 shows the observed ΔT_{RT} values versus the distance between the reference and the tested modules. Data correspond to the two above described experiment performed in the GS-IES-UPM terrace and also to a measuring campaign in the *El Romero Solar* PV plant, which is described in the next chapter. With this figure in mind, we have postulated the following empirical model:

$$\Delta T_C(d) = \min\{A \cdot \sqrt{d_{RT}}, 10 \text{ }^\circ\text{C}\} \quad (37)$$

where A is a constant equal to $3 \text{ }^\circ\text{C} \cdot \text{m}^{-1/2}$ and d_{RT} is the distance between the centres of the modules. Table 18 details the corresponding standard uncertainty on the temperature estimation. Table 19 and Table 20 extend the exercise to the estimation of uncertainty to the final STC characteristics of the tested modules. It has been considered for these parameters the same Type A uncertainty as for the Solar Box, because in the field measurements the same components of uncertainty are found (spectral mismatch, misalignment, I - V curve extrapolation to STC and temperature correction).

Figure 33. Empirical model resulting from the experiments where the temperature difference between the reference and the tested modules is related to the distance.

Component, i	Input information	Standard Uncertainty $T_{C,TEST} = T_{C,REF}$ (°C)	Standard Uncertainty $T_{C,TEST} = T_{C,REF} + \Delta T_{RT}$ (°C)
Reference module calibration	Uncertainty on the temperature component (50 °C)	$u_B^{Tc(50^\circ C)} = 2.13 \text{ } ^\circ\text{C}$	$u_B^{Tc(50^\circ C)} = 2.13 \text{ } ^\circ\text{C}$
PT1000 at the reference module	Accuracy: $\pm(0.3+0.005 T)=0.55 \text{ } ^\circ\text{C}$	---	$u_B^{Sensor,REF} = 0.318 \text{ } ^\circ\text{C}$
PT1000 at the tested module	Accuracy: $\pm(0.3+0.005 T)=0.55 \text{ } ^\circ\text{C}$	---	$u_B^{Sensor,TEST} = 0.318 \text{ } ^\circ\text{C}$
Non-uniform temperature along the reference module	$\leq 7 \text{ } ^\circ\text{C}$ at other than STC	$u_B^{\Delta T,REF} = 2.021 \text{ } ^\circ\text{C}$	$u_B^{\Delta T,REF} = 2.021 \text{ } ^\circ\text{C}$
Non-uniform temperature along the tested module	$\leq 7 \text{ } ^\circ\text{C}$ at other than STC	$u_B^{\Delta T,TEST} = 2.021 \text{ } ^\circ\text{C}$	$u_B^{\Delta T,TEST} = 2.021 \text{ } ^\circ\text{C}$
Non-uniform temperature along the PV array	Module centre temperature differences up to: $\Delta T_c(d) = \min\{A \cdot \sqrt{d_{RT}}, 10^\circ\text{C}\}$	$u_B^{\Delta T10 (>11m)} = 5.77 \text{ } ^\circ\text{C}$ $u_B^{\Delta T7 (6m)} = 4.04 \text{ } ^\circ\text{C}$ $u_B^{\Delta T3 (adj)} = 1.73 \text{ } ^\circ\text{C}$	---
D.A.S.	Accuracy: $\pm 0.2\%$ Resolution: 12 bits digitization	$u_B^{DAS} = 0.058 \text{ } ^\circ\text{C}$	$u_B^{DAS} = 0.058 \text{ } ^\circ\text{C}$

Table 18. Type B uncertainty components at 50 °C on the estimation of $T_{C,TEST}$.

Uncertainty	I_{SC}^* (%)	V_{OC}^* (%)	P_{MPP}^* (%)	FF^* (%)
<i>Type A</i>	0.43	0.16	0.31	0.24
<i>Type B</i>				
With the Solar Box	0.742	0.365	0.882	0.381
Without the Solar Box $T_{C,TEST} = T_{C,REF}$	1.105	2.285	3.293	1.23
Without the Solar Box $T_{C,TEST} = T_{C,REF} + \Delta T_{RT}$	1.05	1.187	1.915	0.703

Table 19. Type A and Type B in-field uncertainties on the STC electrical components considering that both modules (reference and tested) are located more than 11 m away ($\Delta T_{RT} = \pm 10$ °C).

u_c	I_{SC}^* (%)	V_{OC}^* (%)	P_{MPP}^* (%)	FF^* (%)
With the Solar Box	0.858	0.399	0.935	0.45
Without the Solar Box $T_{C,TEST} = T_{C,REF}$	1.186	2.291	3.308	1.253
Without the Solar Box $T_{C,TEST} = T_{C,REF} + \Delta T_{RT}$	1.135	1.198	1.94	0.743

Table 20. Resulting combined uncertainties on the STC electrical components considering that both modules (reference and tested) are located more than 11 m away ($\Delta T_{RT} = \pm 10$ °C).

3.5.4 ON THE NEED OF A TWIN CAPACITIVE LOAD

The procedure described above uses only the I_{SC} and V_{OC} values of the reference module but not its full I - V curve. Because these values can be obtained by means of conventional multimeters, one can consider the convenience of using a twin instead of a single load.

The motivation for developing twin loads is rooted on past GS-IES-UPM experiences with quality controls of PV module supplies. We got excellent results^[47] with an outdoor method based on the quasi-simultaneous measuring I - V curves of a tested module and of an adjoining reference module. Then, both curves were extrapolated to STC in accordance with IEC-60891 using the G given by a reference solar cell and estimating T_C from the ambient temperature, T_A and the NOCT. This way, the corresponding measured STC powers, $P_{MPP,TEST,m}^*$ and $P_{MPP,REF,m}^*$, respectively, were derived. The core of the method was an additional correction for accommodate the corresponding calibration value, $P_{MPP,REF,CAL}^*$ (previously given by an independent and

accredited laboratory). This way, the finally assigned STC power to the tested module, $P_{MPP,TEST,ASSIGNED}^*$, was given by:

$$P_{MPP,TEST,ASSIGNED}^* = P_{MPP,TEST,m}^* \cdot \frac{P_{MPP,REF,CAL}^*}{P_{MPP,REF,m}^*} \quad (38)$$

The underlying assumption of this method was that errors associated with the extrapolation from real to STC (spectrum and cell temperature effects) and with the determination of the real operation conditions (irradiance and ambient temperature calibration sensors) are the same in two adjoining and equal PV modules.

The twin capacitive load can be understood as a further improvement of this method, assuring simultaneity and also avoiding additional sensors for G and T_C . Now, the hope is that using I_{SC} and V_{OC} for estimating G and T_C must avoid spectral and T_C determination issues. Consequently, $P_{MPP,REF,m}^*$ must essentially be equal to $P_{MPP,REF,CAL}^*$. Hence, in principle neither measuring the I - V curve of the reference module nor the additional correction are needed. However, we still have decided to maintain both the I - V measurement and the correction as a precaution for compensating for possible FF errors due to non-uniform temperature distribution along the PV modules.

Our present PV module testing experience with this method, limited to the above described tests on the GS-IES-UPM terrace and on the 246 MW_p *El Romero Solar* PV plant (described in next chapter), is that such additional FF correction is typically below 0.5%, which is insignificant even on the uncertainty context associated to the characterization with the Solar Box (see section 3.3.4.3). That suggests such correction is not needed and, therefore, that the twin capacitive load is an unjustifiable sophistication. However, we still keep on the use of this twin load meanwhile the experience with the method increases and become conclusive. It is opportune mentioning that this device entails non negligible practical advantages, in terms of reliability (measurements can follow even on case of a broken channel) and measurement speed (two PV modules can be measured at the same time).

4. FIELD MEASUREMENTS

4.1 INTRODUCTION

This chapter describes the PV modules and array measurements we have performed in the 246 MW_p *El Romero Solar* PV plant located in the Atacama Desert (Chile), with the aim of checking the applicability and usefulness of the instruments and measuring methods described in the chapters above. For that we have performed three different activities: contrasting the G and T_C GS-IES-UPM calibrations of reference modules with the ones from the widely recognized TÜV laboratory, applying the in-field PV module STC characterization up to distances (between the tested module and the reference one) of 16 m and measuring I - V curves larger than 1 MW.

4.2 GS-IES-UPM CALIBRATION COMPARISON

El Romero Solar PV plant has two sets of reference modules. One consists of 20 modules prepared by *Enertis Solar* enterprise and calibrated by TÜV-Shanghai laboratory. The other consists of 6 PV modules prepared and calibrated by the GS-IES-UPM. All these modules are able of providing both G_{ef} and T_C signals. That has led us a nice additional opportunity to contrast our calibrations with a worldwide widely recognized organization. For that, we have prepared a specific supporting structure (Figure 34) able of accommodating 6 coplanar modules, and we have compared the corresponding G_{ef} and T_C 1 minute records along a full day. The experiment was performed on two different days for different combinations of 4 (TÜV) and 2 (GS-IES-UPM) PV modules. One of the TÜV modules was selected as common reference for the two days (TÜV1).

Figure 34. Structure for PV module calibration performed at the PV plant.

4.2.1 IRRADIANCE

As a representative example, Figure 35 shows the G_{ef} readings of two modules, calibrated by TÜV and GS-IES-UPM respectively. The corresponding values of the MBE (Mean Bias Error) and the RMSE (Root Mean Square Error) are 0.239% and 0.389% for incident angles, $\theta_s < 50^\circ$. Table 21 summarizes the same results for all the PV modules and for the two days. The coincidence is outstanding. The RMSE values are below the standard uncertainty estimated in the previous chapter (0.93%).

May 27th, 2017			May 30th, 2017		
Module	MBE (%)	RMSE (%)	Module	MBE (%)	RMSE (%)
TÜV2	0.743	0.957	TÜV5	0.846	0.894
TÜV3	0.440	0.470	TÜV6	0.010	0.089
TÜV4	0.073	0.503	TÜV4	0.078	0.321
GS-IES-UPM1	0.609	0.792	GS-IES-UPM3	0.141	0.413
GS-IES-UPM2	0.239	0.389	GS-IES-UPM4	0.195	0.413

Table 21. MBE and RMSE (in %) of each PV module of TÜV and GS-IES-UPM with respect to the reference (TÜV1) for effective irradiance measurements on May 27th and 30th, 2017, for $\theta_s < 50^\circ$ ($\approx G_{\text{ef}} > 550 \text{ W/m}^2$).

Figure 35. Effective irradiance obtained by a PV module calibrated by GS-IES-UPM plotted versus the effective irradiance obtained by the reference module calibrated by the TÜV (purple), and differences between both effective irradiances (yellow). Measurements have been recorded on May 27th, 2017, for $\vartheta_s < 50^\circ$ ($\approx G_{ef} > 550 \text{ W/m}^2$).

4.2.2 TEMPERATURE

Figure 36 shows the T_C differences between the readings from the same modules of Figure 35. Corresponding MBE and RMSE are 1.9°C and 1.9°C , respectively. Table 22 summarizes the results for all the modules and for the two days. The distance between the centres of the modules is also given. The key point is that the differences in temperature are inside the expected range (the dispersion of temperature along a PV array is below 7°C for 5 m, Figure 33). Hence, the GS-IES-UPM and TÜV calibrations are again in good coherence.

May 27th, 2017				May 30th, 2017			
Module	Distance (m)	MBE (°C)	RMSE (°C)	Module	Distance (m)	MBE (°C)	RMSE (°C)
TÜV2	5	-2.0	2.7	TÜV5	5	-0.5	1.6
TÜV3	3	-1.6	2.3	TÜV6	3	-2.4	2.7
TÜV4	2	-0.9	1.3	TÜV4	2	0.2	0.9
GS-IES-UPM1	4	0.0	1.6	GS-IES-UPM3	4	3.7	4.0
GS-IES-UPM2	1	1.9	1.9	GS-IES-UPM4	1	0.4	1.1

Table 22. MBE and RMSE (in °C) of each PV module of TÜV and GS-IES-UPM with respect to the reference (TÜV1) for cell temperature measurements on May 27th and 30th, 2017, for $\theta_s < 50^\circ$ ($\approx G_{\text{ef}} > 550 \text{ W/m}^2$).

Figure 36. Differences (°C) in cell temperature obtained by a PV module calibrated by GS-IES-UPM and by the reference module calibrated by the TÜV. Measurements have been recorded on May 27th, 2017, for $\theta_s < 50^\circ$ ($\approx G_{\text{ef}} > 550 \text{ W/m}^2$).

4.3 PV MODULE MEASUREMENTS

El Romero Solar PV plant is composed of about 800000 polycrystalline silicon modules from two different manufacturers: Hareon Solar (4BB-HR 315P) of 315 W and JA Solar (JAP6 72/315/3BB and JAP6 72/320/3BB) of 315 and 320 W, respectively. As part of the Quality Assurance Procedure, QAP, a sample of 50 modules has been selected from each batch of 10000 and submitted to independent STC power controls at the factory output. These controls were performed with the solar simulator of the TÜV-Shangai laboratory. After two months of sun exposition, at the own PV plant, another control has been performed with a portable solar simulator of *Enertis Solar*. In average, the power measured after the sun exposition is 2.5% less than the measured at the factory output, which must likely be due to initial degradation caused by LID^[78] (Light Induced Degradation).

The QAP of this PV plant extends to its lifetime and foresees the periodical measure of these 4000 modules, in principle, by means of a portable solar simulator. Needless to say, it will require dismounting and mounting again all the PV modules from their respective operation positions, which is time consuming task and exists the possibility of module damage during it. In order to facilitate this task, all the modules are installed together in a same sector of the PV plant. Despite non-intentionally, that created a nice opportunity for checking the feasibility of the outdoor testing procedure proposed in this thesis, comparing its features and its results with the previously obtained with the portable solar simulator.

It is opportune remembering that the here considered procedure fully avoid handling and moving the PV modules. The only preparation for testing a module consist on disconnecting it from the PV array (in other words, on open its two plugs) and on installing a coplanar reference module at a certain distance. In particular, we have managed with distances up to 16 m, and we have installed the reference module on a PV array side edge. This arrangement (Figure 37) allowed for testing 56 modules using the same position for the reference module. Just for convenience, we have disregarded a column of 8 PV modules, because the proximity of a supporting structure crossbeam makes difficult the task of disconnecting the modules.

Figure 37. (a) Reference module (REF) and PV modules to be tested (front view). These modules have been numbered from top to bottom and from the perimeter to the inside of the array. (b) Schematic of the distribution of the modules to be tested (rear view). (c) PV modules disconnected ready to be measured.

A first practical consideration is that just installing the reference module on the upper edge would allow of testing more than 100 modules still using the same PV

module position. And we think this still have the potential to significantly increase, just at the price of enlarging the wires of the twin capacitive load.

It is important to comment that at the starting of the measuring campaign we still were scarcely conscious of the advantages of deriving the T_C of the tested module, $T_{C,TEST}$, by correcting the value measured at the reference module with the difference on the temperature observed at its respective centres, ΔT_{RT} . That explain why our main concern when preparing the travel to Chile was to check how many modules we could measure in a same day but without considering the ΔT_{RT} correction. It must be noted that the condition $G > 800 \text{ W/m}^2$ limited the useful period to three hours per day, which can be considered as the worst situation because the PV arrays are static ones and we performed the measurements on winter season. In this regard, the good news was that, once all the PV modules were disconnected from the array, just two persons (the author of this thesis handling with the load and a technician of the PV plant handling the wires) were able of measuring up to 280 modules per day. That was beyond our expectations and, taking into account that it was our first attempt, we think again this figure has the potential to significantly increase. However, we soon realized that the P_{MPP}^* differences between our results and the corresponding from the portable solar simulator significantly increased with distance, reaching more than 3% for distances of about 16 m, as Figure 38 shows. The differences depicted in this figure are the average of 15 measurements performed on different moments of 11 days. Corresponding individual values reached even 3.80%.

Figure 38. R_{MP}^* differences (in %) between the average of 15 measurements of each module extrapolated to STC (according to IEC-60891) measured with the twin capacitive load and the value obtained with the portable solar simulator. These measurements have been carried out without correcting the temperature ($T_{C,TEST} = T_{C,REF}$ –procedure presented in the previous chapter). The measurements were performed between May 30th and June 9th, 2017. Green colour is related to lower absolute differences, while red colour is related to higher absolute differences.

Even being reasonable for other purposes, 3% is not satisfactory for rigorous QAP. That provides the motivation for study the T_C difference between the reference and the tested modules which, in turns, led us to the idea of correcting $T_{C,TEST}$ with the ΔT_{RT} observed by means of two PT1000. That happens when our time in *El Romero* was approaching the end, and we just had a limited number of PT1000, 8 in particular. Then, still having the worry of measuring quickly in mind, we decided to proceed just testing 7 modules and keeping the corresponding PT1000 (the other PT1000 was used at the reference module) stuck to their back surfaces all along the measuring campaign. This time, the differences between our results and the corresponding from the portable solar simulator become lower than 2%. Figure 39 shows the position of the 7 PV modules and the corresponding differences. The values shown in this figure are the averages of 22 measurements performed along 5 days. Figure 40 shows the median of the 22 difference values for each module. In the case of the most distant module, it can be seen that single differences have reached 2.69%. Hence, a practical consideration is that measurements on a same module must be repeated several times; let us say three or four times. Even recognizing the limited number of modules involved in this experiment, we have confidence that the results are satisfactory enough for validating the here proposed method as a nice alternative to in-field measurements with portable solar simulators.

Further measurements in the GS-IES-UPM terrace (already described in chapter 3) are supporting such confidence.

Figure 39. R_{MPP}^* differences (in %) between the average of 22 measurements of each module extrapolated to STC (according to IEC-60891) measured with the twin capacitive load and the value obtained with the portable solar simulator. These measurements have been carried out taking into account the temperature difference ($T_{C,TEST} = T_{C,REF} + \Delta T_{RT}$). The measurements were performed between June 5th and June 9th, 2017. Green colour is related to lower absolute differences, while red colour is related to higher absolute differences.

Figure 40. Medians (red lines) of the 22 differences (in %) of R_{MPP}^* values for each module measured with the twin capacitive load and extrapolated to STC (according to IEC-60891) and the value obtained with the portable solar simulator, taking into account the temperature difference between the reference and the tested modules. The boxes delimit the 95% confidence interval and the horizontal lines show the maximum and minimum differences.

It is worth mentioning that IR temperature sensors, instead of PT1000, likely allow measuring as quickly as disregarding any variation of temperature, because they require neither direct contact with the back module surface nor appreciable stabilization time, and their readings can be easily integrated in the automatic data acquisition process at the twin load. In fact, we have approach such solution trying with the IR camera we normally use for detecting hot-spots at PV arrays. Figure 41 shows the average temperature seen by the camera over a region close to the centre and selected in such a way that thermal anomalies caused by crossbars, PT1000, etc. are avoided. The readings from the camera and from the PT1000 differ about only 0.1 °C.

Figure 41. Temperatures measured simultaneously by the thermographic camera and the PT1000 for the reference module and module M25.

Finally, we check the possibility of avoiding the ΔT_{RT} correction by assuring both modules (reference and tested) are at the ambient temperature. For that, we cover the modules with an opaque and white blanket during at least half an hour before starting the measurements (Figure 42). In practice, this method performs very slowly, because the reference module heats on each measurement and is necessary waiting it cools again after covering it for measuring the next module. As a representative example, Table 23 shows the resulting P_{MPP}^* for two different modules along the temperature range between 18 and 34 °C. Differences from cooling or not (Table 24) are below than 0.15%, which do not justify the associate procedure complexity and time increase.

Figure 42. PV reference (REF) and tested (M08 and M32) modules of the array covered with an opaque and white blanket (avoiding receive solar radiation) prepared for the measurements at 25 °C.

	Module	Portable Solar Simulator	GS-IES- UPM	
		P_{MPP}^* (W)	P_{MPP}^* (W)	Difference (%)
25 °C	M08	308.6	309.1	0.15
	M32	311.8	311.2	-0.18
18 to 34 °C	M08	308.6	308.9	0.10
	M32	311.8	310.9	-0.29

Table 23. Results obtained from the measurement at 25 °C and between 18 and 34 °C of modules M08 and M32. The measurements have been extrapolated to STC taking into account ΔT_{RT} .

GS-IES-UPM	P_{MPP}^* (25 °C) (W)	P_{MPP}^* (50 °C) (W)	Difference (%)
M08	309.1	308.6	0.15
M32	311.2	311.2	0.01

Table 24. Comparison between the obtained P_{MPP}^* from the measurement performed at 25 °C and the average of 22 measurements performed close to 50 °C (modules M08 and M32).

4.4 MEASURING LARGE POWER I-V CURVES

Measuring I - V curves of large PV arrays is far of being considered in current PV engineering practices. Their possible usefulness for array characterization is likely low, because the uncertainty due to the T_C dispersion is still larger than commented above for the measurement of PV modules. Moreover, misalignments among different supporting

structures of a same array are commonly found (Figure 43). That makes G_{ef} to be non-uniform along the PV array surface, given raise to an additional source of uncertainty. However, large power I - V curves can still be useful for other purposes. In particular, we took profit of the test campaign we performed in *El Romero Solar* PV plant for attempting the use of such curves as an instrument for looking in-deep on the relation between the I - V curve parameters (I_{SC} , V_{OC} , series and shunt resistances and diode ideality factor) and the operation conditions (G_{ef} and T_{C}). This attempt was finally hindered by shading appearing in the PV plant on winter during a significant part of the day. Such shading is inherent to the PV plant layout (tilt angle and distance between rows) and fully coherent with economic optimization. But it made impossible for us obtaining non-anomalous I - V curves with irradiances lower than 600 W/m^2 . Nevertheless, we obtained I - V curves larger than 1 MW for the first time in the world, which has led us to include here a brief description of this experience, even recognizing that this fact does not likely rise above the anecdotal.

Figure 43. Misalignments among different supporting structures of a same array.

El Romero Solar PV plant is composed of 1 MW inverters. The inverter DC input consists on the parallel association of 8 lines, each receiving the power from 540 PV modules (20 in series x 27 in parallel). We have taken profit of an existing contact

for factory proofing that allows accessing the inverter input after the parallel of the 8 lines, i.e. at the poles of the full PV array.

The capacitive load (section 2.2.2) was connected to the positive and negative poles of a PV array just at the inverter entry (Figure 44). So, the corresponding results include all the losses until this point (possible module degradation, mismatching, DC wiring, etc.). Heavy rains the week before the measurements cleaned the modules, which have ensured that the generator is free of dirt on its surface (that is, soiling losses are negligible). A calibrated resistor class 0.5 with a relation $1000 \text{ V} / 150 \text{ mV}$ ($0.15 \text{ m}\Omega$) was included in the negative pole in order to measure the DC current.

Figure 44. Connections made at the inverter entry. (a) Positive pole of the inverter. (b) Negative pole of the inverter and calibrated resistor ($1000 \text{ A} / 150 \text{ mV}$, $0.15 \text{ m}\Omega$). (c) Capacitive load and oscilloscope connected to the inverter.

Table 25, Table 26, Figure 45 and Figure 46 describe the relevant data associated to the largest power I - V curve we could obtain. It is worth commenting that despite the uncertainty suspicious mentioned above, the averaged resulting STC power obtained from several I - V curves, 1321.1 kW , is very close to the corresponding value obtained in a different experiment^[37] based on the simultaneous measure of P_{DC} , G_{ef} and T_{C} along a relatively long period. The large number of records in the latter (1 minute records have been obtained during more than one hour) suggests a relatively low uncertainty. The resulting STC power was 1315.2 kW , which differs less than 1% of the value from the I - V curve. That can be understood as the more recent step on the GS-IES-UPM tradition with large I - V curves. In particular, 500 kW ^[31] and 800 kW ^[32] I - V

curves were obtained in 2012. However, we do not dare claiming general accuracy for our large I - V curves, because we recognize the back experience is still short.

Location	Atacama Desert (Chile)	$G_{\text{horizontal}}$ (W/m^2)	668
Date	25/05/2017 12:33:00	Ambient Temp. ($^{\circ}\text{C}$)	13
Altitude (m)	1124	Wind speed (m/s)	2
Barometric pressure (bar)	0.88	Wind direction ($^{\circ}$)	336
Air Mass	1.36	Relative humidity (%)	65

Table 25. Meteorological conditions at the moment of the I - V curve measurement.

	I_{SC} (A)	V_{OC} (V)	I_{MPP} (A)	V_{MPP} (V)	P_{MPP} (kW)	FF
Measured	1663	819	1535	652	1001	0.735
Extrapolated to STC ^k	1930	873	1801	728	1311	0.779
$G_{\text{ef}} = 853 \text{ W}/\text{m}^2$			$T_{\text{C}} = 40.1 \text{ }^{\circ}\text{C}$			

Table 26. Measured and extrapolated to STC (according to the IEC-60891) electrical parameters of the 1 MW I - V curve.

Figure 45. Evolution of the measured current (red) and voltage (yellow) during the charging process.

^k These results were published in the press^{[81]–[83]} at the beginning of September 2017. Unfortunately, in these figures the number of parallel strings in the array was not taken into account when extrapolating to STC. The values here presented have been already corrected.

Figure 46. Measured I - V curve (blue) and extrapolated to STC (orange) according to the IEC-60891.

Just for curiosity, Table 27 shows I - V curves affected by shades.

Time	Shadow	I - V curve
Without shades 12:33 $G_{\text{ef}} = 853 \text{ W/m}^2$ $T_c = 40.1 \text{ }^\circ\text{C}$ $P_{\text{MPP}} = 1000.8 \text{ kW}$		
15:44 $G_{\text{ef}} = 506 \text{ W/m}^2$ $T_c = 34.3 \text{ }^\circ\text{C}$ $P_{\text{MPP}} = 552.7 \text{ kW}$		
16:51 $G_{\text{ef}} = 231 \text{ W/m}^2$ $T_c = 21.7 \text{ }^\circ\text{C}$ $P_{\text{MPP}} = 220 \text{ kW}$		

Table 27. Shading effects on the PV array.

5. CONCLUSIONS AND FUTURE LINES OF RESEARCH

5.1 CONCLUSIONS

The title of this thesis, “*Lowering uncertainty on outdoor characterization of PV modules and calibration of PV reference devices*” is a proper synopsis of its objectives. Figure 47 shows the chain of devices and procedures involved on that characterization and calibration.

Figure 47. Laboratory and in-field characterization and calibration procedures.

The main contributions of this thesis are:

- The uncertainty on the calibration of the reference cell, used for measuring irradiance and linking the traceability of the GS-IES-UPM calibrations to the International System of Units (S.I.), has been minimized by combining different independent calibrations. Table 28 shows the reduction we got by combining the original calibration, made in the FISE, with other three, made in the CIEMAT, in the 5th international spectro-and broadband radiometer intercomparison and in the own GS-IES-UPM.

Calibration origin	Calibration value [mV/(kW/m ²)]	Standard deviation (%)
Fraunhofer-ISE	92.025	2
CIEMAT	90.354	1.459
5 th international spectro-and broadband radiometer intercomparison	90.796	0.988
GS-IES-UPM	91.089	1.445
<i>Final assigned calibration</i>	<i>90.899</i>	<i>0.67</i>

Table 28. Calibration values and standard deviations of each laboratory and the final assigned calibration value for the reference cell used to measure the irradiance in the characterization and calibration procedures of PV modules.

- A “Solar Box”, that allows the STC characterization of PV modules and also the measurement of the temperature and irradiance coefficients, has been designed and implemented. This is a rather simply home-made device consisting on a thermally-isolated wooden box coupled to a temperature control system and mounted on a metallic structure that allows it to be positioned in azimuth and tilt.
- The uncertainty on the characteristics of crystalline silicon PV modules measured with such reference cell and Solar Box has been carefully analysed, after one year measuring campaign for quantifying Type A uncertainties. Resulting uncertainties, summarized in Table 29, are in the order of those corresponding to high accuracy solar simulators, and allows it the involvement in the Quality Assurance Procedure (QAP) of large PV plants.

$u_c^{P_{MPP}^*}$ (%)	$u_c^{I_{SC}^*}$ (%)	$u_c^{V_{OC}^*}$ (%)	$u_c^{FF^*}$ (%)	u_c^α (%/°C)	u_c^β (%/°C)	u_c^γ (%/°C)	$u_c^{\eta'}$ (%)
0.935	0.858	0.399	0.45	0.015 (25.43%)	0.028 (8.71%)	0.042 (9.88%)	1.21

Table 29. Combined standard uncertainty on the STC parameters and on the temperature coefficients obtained using the Solar Box ($k=1$).

- The uncertainty on the irradiance and module temperature measured with reference modules calibrated with such reference cell and the Solar Box has also been carefully analysed. The resulting combined uncertainty on the irradiance signal is 0.93% for incident angles, $\theta_s, \leq 50^\circ$ (Type A: 0.43%, Type B: 0.82%) and 1.40% for $\theta_s > 50^\circ$ (Type A: 0.43%, Type B: 1.33%), and on the cell temperature signal is 0.399% (Type A: 0.16%, Type B: 0.365%).
- A procedure for in-field STC characterization of PV modules in their own operation positions (i.e., do not requiring PV module handling) has been defined. It is based on translating a measured I - V curve to STC in accordance with IEC-60891. The actual irradiance and cell temperature values are obtained from the I_{SC} and the V_{OC} of a coplanar reference module and with the trick (this is the thesis contribution) of correcting the tested module temperature with the difference of temperature observed at the centres of both PV modules. Corresponding uncertainties have also been estimated, after different experiments performed at the GS-IES-UPM facilities and at the *El Romero Solar*, a 246 MW_p PV plant, and related with the distance between the reference and the tested module. Table 30 shows the resulting uncertainties, which are good enough to contractual power controls of PV modules supply.

u_c	I_{SC}^* (%)	V_{OC}^* (%)	P_{MPP}^* (%)	FF^* (%)
$T_{C,TEST} = T_{C,REF} + \Delta T_{RT}$	1.135	1.198	1.94	0.743

Table 30. Combined uncertainties on the STC electrical components considering that both modules (reference and tested) are located more than 11 m away ($\Delta T_{RT} = \pm 10^\circ\text{C}$) and taking into account the temperature differences between its centres.

- Two capacitive I - V tracers for specific purposes have been designed and developed: a twin capacitive load, which is an I - V tracer capable of obtaining the simultaneous I - V curves of two PV modules; and a 2 MW load, which allows obtaining I - V curves of 2 MW of power.

- Using such 2 MW capacitive load, an I - V curve larger than 1 MW has been obtained. This represents the current world record of power measurement in characterization of PV arrays.

5.2 FUTURE LINES OF RESEARCH

We believe on the usefulness of outdoors and in-field PV testing for a sound PV widespread deployment. Hence, looking for reinforce the credibility of such testing, we propose the following future goals:

- Extending the availability of primary reference solar cells. Those are devices on the origin of S.I. traceable calibration chains and consisting on a c-Si solar cell (2 x 2 cm, float-zone silicon) with an encapsulation of specific features^[79]. Their calibration typically encompasses a standard deviation of less than 0.2%. As far as we know, no Spanish organization disposes of a primary reference cell. However, the IES-UPM has the capability of doing it. That would allow reducing uncertainty on current PV calibration procedures and counteract the current external dependence of all the national PV organizations.
- Performing new experimental campaigns, looking for refining the procedures of module temperature estimation and, hence, to increase the repeatability on PV module STC power results. For that, it is convenient to develop a new twin capacitive load specifically prepared for automatically incorporate the measurement of the temperatures observed at the PV modules back surface.
- Officially accrediting the here proposed procedures for outdoor testing of PV modules and calibration of reference modules, in order to facilitate their use on Quality Assurance Procedures linked to the bankability of PV systems.
- Extending the uncertainty estimation procedures from the measurement of single PV modules to larger PV arrays.

APPENDIX A. CALCULATION OF UNCERTAINTY

A.1 BASIC CONCEPTS

This appendix attempts to clarify any doubts that may arise to the reader in the calculation of the uncertainties along this document. Most of the information has been obtained from the Guide to the expression of uncertainty in measurement^[58]. “*Measurement uncertainty*” can be defined as an estimate characterizing the range of values within which the true value of a measurand lies. So, when a result is presented, it should be composed of a number which represents the most probable value, the units (those used in different sciences and technologies) and an interval around this value in which the true value of the measured magnitude has a certain probability of being found. For example, if a calibration laboratory gives the power value for a measured PV module it should present something like:

$$250 \text{ W} \pm 2.5\% \text{ (confidence interval of 95\%)} \quad (39)$$

This means that the power which is expected to deliver the PV module is between $250 \text{ W} - 2.5\%$ and $250 \text{ W} + 2.5\%$ with a 95% of probability. Besides, the most probable value inside this interval is 250 W . As the laboratory reports that the confidence interval is 95%, it is claiming that this 2.5% is related to an expanded uncertainty. Other possibilities to express the uncertainty are the typical uncertainty or the combined standard uncertainty.

TYPICAL UNCERTAINTY

The typical uncertainty must be evaluated in two ways: Type A and Type B.

Type A uncertainty (u_A) is defined as the standard deviation (σ) of the measured magnitude from a number N of repeated and independent observations, being the expectation (μ) the average of the values obtained in the N observations. Type A uncertainty is commonly known as random or accidental error, which is the inevitable error that occurs by unique events and impossible to control during the measurement procedure. To reduce this type of uncertainty, it is necessary to increase the number of measurements and the size of the sample.

Type B uncertainty (u_B) is the one which is established by scientific decision based on all available information about the possible variability of a quantity which we measure and not from repeated observations. It is obtained from the manufacturer's specifications of the measuring devices, calibration certificates or other similar sources. This type of uncertainty is also known as systematic error, and is one which occurs in the same way in all measurements which are made of a magnitude. It may be originated as a defect of the measuring instrument or by a particularity of the measurement process.

The Type B uncertainty may be expressed as multiples of the standard deviation or as a range corresponding to a confidence level (90, 95 or 99%) represented by a normal distribution (Figure 48). If only the limits of the interval can be estimated and the probability that the value is within these limits is 1 (and, therefore, outside these limits the probability is 0), it must be presented by a square distribution (Figure 49).

Figure 48. Normal or Gaussian distribution.

Figure 49. Rectangular distribution.

For these distributions, we define the expectation (μ) as the average of the values, and its typical uncertainty is σ for a Gaussian distribution and is $a/\sqrt{3}$ for a rectangular distribution.

COMBINED STANDARD UNCERTAINTY

When a variable y depends on the behavior of other variables, $y(x) = f(x_1, x_2, \dots, x_N)$, the combined uncertainty can be calculated using the *law of propagation of uncertainty*, which is defined as:

$$u_c(y) = \sqrt{\sum_{i=1}^N \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i)} \quad (40)$$

The cited law analyzes the variation of y produced by a small variation of Δx_i in the input estimation x_i .

The total combined standard uncertainty (u_c) must encompass all the uncertainties Type A and Type B which affects to the variable measured. It is calculated by the square root of the Type A uncertainty squared and the sum of the Type B uncertainties squared.

$$u_c = \sqrt{u_A^2 + \sum_i (u_B^i)^2} \quad (41)$$

EXPANDED UNCERTAINTY

The expanded uncertainty is the combined uncertainty multiplied by a coverage factor (k).

$$U = k \cdot u_c \quad (42)$$

This coverage factor determines the confidence interval (Table 31), where the confidence interval is the one in which the probability is highest to find the true value. The most common value for k is 2.

Coverage factor (k)	Confidence interval (%)
1	68
2	95
3	99

Table 31. Coverage factor corresponding to each confidence level.

The result of a measurement is the conveniently expressed as $Y = y \pm U$, which is interpreted to mean that the best estimate of the value attributable to the measurand Y is y , and that $y - U$ to $y + U$ is an interval that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to Y .

A.2 UNCERTAINTY CALCULATION

This section shows the calculation of the uncertainties in a detailed way for the measurement in the Solar Box at 1000 W/m² and 25 °C.

TYPE A UNCERTAINTY

The Type A uncertainty has been calculated as the standard deviation of the measurements made during a year in the Solar Box for each measured parameter (Table 32).

$u_A^{P_{MPP}^*}$ (%)	$u_A^{I_{MPP}^*}$ (%)	$u_A^{V_{MPP}^*}$ (%)	$u_A^{I_{SC}^*}$ (%)	$u_A^{V_{OC}^*}$ (%)	$u_A^{FF^*}$ (%)	u_A^α (%/°C)	u_A^β (%/°C)	u_A^γ (%/°C)	$u_A^{\eta_{0.6}}$ (%)	$u_A^{\eta_{0.2}}$ (%)
0.31	0.40	0.21	0.43	0.16	0.24	0.008 (13.33%)	0.010 (3.13%)	0.019 (4.41%)	0.50	0.68

Table 32. Standard deviation (in %) of the characteristic parameters measured on a same PV module 15 times over a year.

TYPE B UNCERTAINTY

When Type B uncertainty is analyzed, uncertainties for all measuring equipment used in the procedure must be determined.

IRRADIANCE

The uncertainty sources in the determination of the effective irradiance, obtained by an ISET calibrated cell of monocrystalline silicon, are:

- u_B^{RCC} : uncertainty of the calibration value on the short-circuit current of the reference cell:

$$u_B^{RCC} = 0.67\% \quad (43)$$

- $u_B^{Dat,Res}$: uncertainty due to the resolution of the datalogger (analog/digital conversion - 20 bits):

$$u_B^{Dat,Res} = \frac{Full\ Scale}{2^{21}} \quad (44)$$

- $u_B^{Dat,Acc}$: uncertainty due to the accuracy of the datalogger, where V is the measured signal, T is the operating temperature of the datalogger (ambient temperature, between 18 and 28 °C), TO is the normal operating temperature (23 °C) and FS the Full Scale.

$$u_B^{Dat,Acc} = 0.005\% \cdot V(1 + 0.0005(T - TO)) + 0.004\% \cdot FS(1 + 0.0005(T - TO)) \quad (45)$$

Assuming the uncertainties corresponding to the measurement equipment follow a rectangular distribution function, the uncertainty on the irradiance is:

$$u_B^{Gef} = \sqrt{(u_B^{RCC})^2 + \left(\frac{u_B^{Dat,Res}}{\sqrt{3}}\right)^2 + \left(\frac{u_B^{Dat,Acc}}{\sqrt{3}}\right)^2} \quad (46)$$

$$u_B^{Gef} = \sqrt{(0.67)^2 + \left(\frac{5.25 \cdot 10^{-5}}{\sqrt{3}}\right)^2 + \left(\frac{9.4 \cdot 10^{-3}}{\sqrt{3}}\right)^2} = 0.67\% \quad (47)$$

CELL TEMPERATURE

The uncertainty sources that affect the measurement of the temperature of operation of the cells are:

- u_B^{PT1000} : uncertainty due to the accuracy of temperature sensors.

$$u_B^{PT1000} = 0.3 + 0.005|T| \quad (48)$$

- $u_B^{\Delta T3}, u_B^{\Delta T7}$: uncertainties in the non-uniformity of temperature on the surface of the PV module. The maximum temperature difference between the readings of the 9 PT1000 glued to the back surface of the PV module when the measurement is performed at 25 °C is equal to 3 °C and the difference at other conditions than STC is 7 °C.

$$\begin{aligned} u_B^{\Delta T3} &= 1.5 \text{ °C} \\ u_B^{\Delta T7} &= 3.5 \text{ °C} \end{aligned} \quad (49)$$

- u_B^{BTC} : uncertainty due to backskin to cell thermal drop. The difference is between 2 and 3 °C^{[52], [53], [80]}.

$$u_B^{BTC} = 1 \text{ °C} \quad (50)$$

- $u_B^{Dat,Res}$: uncertainty due to the resolution of the datalogger (analog/digital conversion - 20 bits):

$$u_B^{Dat,Res} = \frac{Full\ Scale}{2^{21}} \quad (51)$$

- $u_B^{Dat,Acc}$: uncertainty due to the accuracy of the datalogger. T is the operating temperature of the datalogger (ambient temperature, between 18 and 28 °C) and TO is the normal operating temperature (23 °C).

$$u_B^{Dat,Acc} = 0.003(T - TO) \quad (52)$$

Assuming that all uncertainties follow a rectangular distribution, the uncertainty on the cell temperature measurement will be equal to:

$$u_B^{T_C(STC)} = \sqrt{\left(\frac{u_B^{PT1000,STC}}{\sqrt{3}}\right)^2 + \left(\frac{u_B^{\Delta T3}}{\sqrt{3}}\right)^2 + \left(\frac{u_B^{BTC}}{\sqrt{3}}\right)^2 + \left(\frac{u_B^{Dat,Res}}{\sqrt{3}}\right)^2 + \left(\frac{u_B^{Dat,Acc}}{\sqrt{3}}\right)^2} \quad (53)$$

$$u_B^{T_C(STC)} = \sqrt{\left(\frac{0.425}{\sqrt{3}}\right)^2 + \left(\frac{1.5}{\sqrt{3}}\right)^2 + \left(\frac{1}{\sqrt{3}}\right)^2 + \left(\frac{1.98 \cdot 10^{-4}}{\sqrt{3}}\right)^2 + \left(\frac{0.06}{\sqrt{3}}\right)^2} \\ = 1.07^\circ\text{C} \quad (4.3\%) \quad (54)$$

$$u_B^{T_C(50^\circ\text{C})} = \sqrt{\left(\frac{u_B^{PT1000,50^\circ\text{C}}}{\sqrt{3}}\right)^2 + \left(\frac{u_B^{\Delta T7}}{\sqrt{3}}\right)^2 + \left(\frac{u_B^{BTC}}{\sqrt{3}}\right)^2 + \left(\frac{u_B^{Dat,Res}}{\sqrt{3}}\right)^2 + \left(\frac{u_B^{Dat,Acc}}{\sqrt{3}}\right)^2} \quad (55)$$

$$u_B^{T_C(50^\circ\text{C})} = \sqrt{\left(\frac{0.55}{\sqrt{3}}\right)^2 + \left(\frac{3.5}{\sqrt{3}}\right)^2 + \left(\frac{1}{\sqrt{3}}\right)^2 + \left(\frac{1.98 \cdot 10^{-4}}{\sqrt{3}}\right)^2 + \left(\frac{0.06}{\sqrt{3}}\right)^2} \\ = 2.13^\circ\text{C} \quad (4.3\%) \quad (56)$$

MEASURED PARAMETERS

When we talk about the measured parameters we refer to the current, voltage and power measured by an oscilloscope of 4 isolated channels and with a resolution of 12 bits. The uncertainties calculated below for I_{SC} and V_{OC} are considered the same as for I_{MPP} and V_{MPP} , respectively.

Current

The sources of uncertainty in the measured current are:

- $u_B^{Osc,Res}$: uncertainty due to oscilloscope resolution (analog/digital conversion with 12 bits).

$$u_B^{Osc,Res} = \frac{FullScale}{2^{13}} \quad (57)$$

- $u_B^{Osc,Acc}$: uncertainty due to the accuracy of the oscilloscope in the measurement of current through the calibrated resistor.

$$u_B^{Osc,Acc} = 0.002 \cdot |I(mV)| \quad (58)$$

- u_B^{Res} : uncertainty due to the calibrated resistor used for current measurement (accuracy 0.5%).

$$u_B^{Res} = 0.005 \cdot |I(mV)| \quad (59)$$

Assuming that all uncertainties follow a rectangular distribution function, the uncertainty on the measurement of the current is:

$$u_B^{I_{SC,m}} = \sqrt{\left(\frac{u_B^{Osc,Res}}{\sqrt{3}}\right)^2 + \left(\frac{u_B^{Osc,Acc}}{\sqrt{3}}\right)^2 + \left(\frac{u_B^{Res}}{\sqrt{3}}\right)^2} \quad (60)$$

$$u_B^{I_{SC,m}} = \sqrt{\left(\frac{0.02}{\sqrt{3}}\right)^2 + \left(\frac{0.2}{\sqrt{3}}\right)^2 + \left(\frac{0.5}{\sqrt{3}}\right)^2} = 0.311\% \quad (61)$$

Voltage

The sources of uncertainty for measured voltage are:

- $u_B^{Osc,Res}$: uncertainty due to oscilloscope resolution (analog/digital conversion with 12 bits).

$$u_B^{Osc,Res} = \frac{FullScale}{2^{13}} \quad (62)$$

- $u_B^{Osc,Acc}$: uncertainty due to the accuracy of the oscilloscope in the measurement of voltage.

$$u_B^{Osc,Acc} = 0.002 \cdot |V| \quad (63)$$

Assuming that the uncertainties follow a rectangular distribution, the uncertainty on the measurement of the voltage is:

$$u_B^{V_{OC,m}} = \sqrt{\left(\frac{u_B^{Osc,Res}}{\sqrt{3}}\right)^2 + \left(\frac{u_B^{Osc,Acc}}{\sqrt{3}}\right)^2} \quad (64)$$

$$u_B^{V_{OC,m}} = \sqrt{\left(\frac{0.02}{\sqrt{3}}\right)^2 + \left(\frac{0.2}{\sqrt{3}}\right)^2} = 0.116\% \quad (65)$$

Power

The sources of uncertainty on the measured power is related to the current and voltage ones, taking into account the law of propagation of uncertainty ($P = V \cdot I$):

$$u_B^{P_{MPP,m}} = \sqrt{\left(u_B^{I_{SC,m}}\right)^2 + \left(u_B^{V_{OC,m}}\right)^2} \quad (66)$$

$$u_B^{P_{MPP,m}} = \sqrt{(0.311)^2 + (0.116)^2} = 0.332\% \quad (67)$$

TEMPERATURE COEFFICIENTS

The temperature coefficients related to the current, voltage and power are also parameters measured in the Solar Box. The uncertainty has been calculated for an irradiance of 1000 W/m² (as for all other parameters) but the cell temperature, in this case, is between 25 and 50 °C, approximately. This is due to these coefficients are calculated in this range of temperatures: when the Solar Box is uncovered the cell temperature is close to 25 °C, and when the PV module is stabilized in temperature the cell temperature is close to 50 °C.

Temperature coefficient α

The coefficient of variation of the current with the temperature is:

$$\alpha = \frac{1}{I_{SC}^*} \frac{dI_{SC}}{dT_C} = \frac{1}{I_{SC}^*} \frac{I_{SC} - I_{SC}^*}{T_C - T_C^*} \quad (68)$$

Applying the law of propagation of uncertainty:

- $u_B^{T_C}$: uncertainty due to cell temperature.

$$u_B^{T_C} = \frac{\partial \alpha}{\partial T_C} \cdot u_B^{T_C(50^\circ\text{C})} = \frac{1}{I_{SC}^*} \cdot \frac{I_{SC} - I_{SC}^*}{(T_C - T_C^*)^2} \cdot u_B^{T_C(50^\circ\text{C})} \quad (69)$$

- $u_B^{I_{SC,m}}$: uncertainty due to the measured current.

$$u_B^{I_{SC,m}} = \frac{\partial \alpha}{\partial I_{SC}} \cdot u_B^{I_{SC,m}} = \frac{1}{I_{SC}^*} \cdot \frac{1}{T_C - T_C^*} \cdot u_B^{I_{SC,m}} \quad (70)$$

The Type B uncertainty on α corresponds to:

$$u_B^\alpha = \sqrt{\left(\frac{\partial \alpha}{\partial T_C} \cdot u_B^{T_C(50^\circ\text{C})}\right)^2 + \left(\frac{\partial \alpha}{\partial I_{SC}} \cdot u_B^{I_{SC,m}}\right)^2} \quad (71)$$

$$u_B^\alpha = \sqrt{(0.0045)^2 + (0.0124)^2} = 0.013 \frac{\%}{^\circ\text{C}} \quad (21.66\%) \quad (72)$$

Temperature coefficient β

The coefficient of variation of the voltage with the temperature is:

$$\beta = \frac{1}{V_{OC}^*} \frac{dV_{OC}}{dT_C} = \frac{1}{V_{OC}^*} \frac{V_{OC} - V_{OC}^*}{T_C - T_C^*} \quad (73)$$

Applying the law of propagation of uncertainty:

- $u_B^{T_C}$: uncertainty due to cell temperature.

$$u_B^{T_C} = \frac{\partial \beta}{\partial T_C} \cdot u_B^{T_C(50^\circ\text{C})} = \frac{1}{V_{OC}^*} \cdot \frac{V_{OC} - V_{OC}^*}{(T_C - T_C^*)^2} \cdot u_B^{T_C(50^\circ\text{C})} \quad (74)$$

- $u_B^{V_{OC,m}}$: uncertainty due to the measured voltage.

$$u_B^{V_{OC,m}} = \frac{\partial \beta}{\partial V_{OC}} \cdot u_B^{V_{OC,m}} = \frac{1}{V_{OC}^*} \cdot \frac{1}{T_C - T_C^*} \cdot u_B^{V_{OC,m}} \quad (75)$$

The Type B uncertainty on β corresponds to:

$$u_B^\beta = \sqrt{\left(\frac{\partial \beta}{\partial T_C} \cdot u_B^{T_C(50^\circ\text{C})}\right)^2 + \left(\frac{\partial \beta}{\partial V_{OC}} \cdot u_B^{V_{OC,m}}\right)^2} \quad (76)$$

$$u_B^\beta = \sqrt{(0.026)^2 + (0.0045)^2} = 0.026 \frac{\%}{^\circ\text{C}} \quad (8.13\%) \quad (77)$$

Temperature coefficient γ

The coefficient of variation of the power with the temperature is:

$$\gamma = \frac{1}{P_{MPP}^*} \frac{dP_{MPP}}{dT_C} = \frac{1}{P_{MPP}^*} \frac{P_{MPP} - P_{MPP}^*}{T_C - T_C^*} \quad (78)$$

Applying the law of propagation of uncertainty:

- $u_B^{T_C}$: uncertainty due to cell temperature.

$$u_B^{T_C} = \frac{\partial \gamma}{\partial T_C} \cdot u_B^{T_C(50^\circ\text{C})} = \frac{1}{P_{MPP}^*} \cdot \frac{P_{MPP} - P_{MPP}^*}{(T_C - T_C^*)^2} \cdot u_B^{T_C(50^\circ\text{C})} \quad (79)$$

- $u_B^{P_{MPP,m}}$: uncertainty due to the measured power.

$$u_B^{P_{MPP,m}} = \frac{\partial \gamma}{\partial P_{MPP}} \cdot u_B^{P_{MPP,m}} = \frac{1}{P_{MPP}^*} \cdot \frac{1}{T_C - T_C^*} \cdot u_B^{P_{MPP,m}} \quad (80)$$

The Type B uncertainty on γ corresponds to:

$$u_B^\gamma = \sqrt{\left(\frac{\partial \gamma}{\partial T_C} \cdot u_B^{T_C(50^\circ\text{C})}\right)^2 + \left(\frac{\partial \gamma}{\partial P_{MPP}} \cdot u_B^{P_{MPP,m}}\right)^2} \quad (81)$$

$$u_B^\gamma = \sqrt{(0.036)^2 + (0.013)^2} = 0.038 \frac{\%}{^\circ\text{C}} \quad (8.84\%) \quad (82)$$

PARAMETERS EXTRAPOLATED TO STC

The extrapolation to STC of the measured parameters is done by means of mathematical equations. So, the uncertainty of these parameters is obtained with the law of propagation of uncertainty. The uncertainties calculated below for I_{SC}^* and V_{OC}^* are considered the same as for I_{MPP}^* and V_{MPP}^* , respectively.

Current

For the calculation of the uncertainty on I_{SC}^* , all sources of uncertainty which influence this parameter must be taken into account. In Figure 50 can be seen these sources and how they have been added to the uncertainty chain until reaching the final uncertainty.

 Figure 50. Uncertainty sources and uncertainty chain on I_{sc}^* .

The extrapolated to STC current is calculated:

$$I_{sc}^* = I_{sc,m} \cdot \frac{G^*}{G_{ef}} \cdot \frac{1}{1 + \alpha(T_c - T_c^*)} \quad (83)$$

Applying the law of propagation of uncertainty:

- $u_{B,I_{sc}^*}^{G_{ef}}$: uncertainty on I_{sc}^* due to the irradiance.

$$u_{B,I_{sc}^*}^{G_{ef}} = \frac{\partial I_{sc}^*}{\partial G_{ef}} \cdot u_B^{G_{ef}} = \frac{I_{sc,m}}{1 + \alpha(T_c - T_c^*)} \cdot \frac{-1}{G_{ef}} \cdot u_B^{G_{ef}} \quad (84)$$

- $u_{B,I_{sc}^*}^{T_c}$: uncertainty on I_{sc}^* due to cell temperature.

$$u_{B,I_{sc}^*}^{T_c} = \frac{\partial I_{sc}^*}{\partial T_c} \cdot u_B^{T_c(STC)} = I_{sc,m} \frac{-\alpha}{[1 + \alpha(T_c - T_c^*)]^2} \cdot u_B^{T_c(STC)} \quad (85)$$

- $u_{B,I_{SC}^*}^{I_{SC,m}}$: uncertainty on I_{SC}^* due to the measured current.

$$u_{B,I_{SC}^*}^{I_{SC,m}} = \frac{\partial I_{SC}^*}{\partial I_{SC,m}} \cdot u_B^{I_{SC,m}} = \frac{1}{1 + \alpha(T_C - T_C^*)} \cdot u_B^{I_{SC,m}} \quad (86)$$

- $u_{B,I_{SC}^*}^\alpha$: uncertainty on I_{SC}^* due to the coefficient variation of the current with the temperature.

$$u_{B,I_{SC}^*}^\alpha = \frac{\partial I_{SC}^*}{\partial \alpha} \cdot u_B^\alpha = I_{SC,m} \frac{-(T_C - T_C^*)}{[1 + \alpha(T_C - T_C^*)]^2} \cdot u_B^\alpha \quad (87)$$

The Type B uncertainty on the extrapolated to STC current corresponds to:

$$u_B^{I_{SC}^*} = \sqrt{\left(\frac{\partial I_{SC}^*}{\partial G_{ef}} \cdot u_B^{G_{ef}}\right)^2 + \left(\frac{\partial I_{SC}^*}{\partial T_C} \cdot u_B^{T_C(STC)}\right)^2 + \left(\frac{\partial I_{SC}^*}{\partial I_{SC,m}} \cdot u_B^{I_{SC,m}}\right)^2 + \left(\frac{\partial I_{SC}^*}{\partial \alpha} \cdot u_B^\alpha\right)^2} \quad (88)$$

$$u_B^{I_{SC}^*} = \sqrt{(0.67)^2 + (0.064)^2 + (0.311)^2 + (0.014)^2} = 0.742\% \quad (89)$$

Voltage

For the calculation of the uncertainty on V_{OC}^* , all sources of uncertainty which influence this parameter must be taken into account. Figure 51 shows these sources and how they have been added to the uncertainty chain until reaching the final uncertainty.

 Figure 51. Uncertainty sources and uncertainty chain on V_{OC}^* .

The extrapolated to STC voltage is:

$$V_{OC}^* = V_{OC,m} \cdot \frac{1}{1 + \beta(T_C - T_C^*)} \quad (90)$$

Applying the law of propagation of uncertainty:

- $u_{B,V_{OC}^*}^{T_C}$: uncertainty on V_{OC}^* due to cell temperature.

$$u_{B,V_{OC}^*}^{T_C} = \frac{\partial V_{OC}^*}{\partial T_C} \cdot u_B^{T_C(STC)} = V_{OC,m} \cdot \frac{-\beta}{[1 + \beta(T_C - T_C^*)]^2} \cdot u_B^{T_C(STC)} \quad (91)$$

- $u_{B,V_{OC}^*}^{V_{OC,m}}$: uncertainty on V_{OC}^* due to the measured voltage.

$$u_{B,V_{OC}^*}^{V_{OC,m}} = \frac{\partial V_{OC}^*}{\partial V_{OC,m}} \cdot u_B^{V_{OC,m}} = \frac{1}{1 + \beta(T_C - T_C^*)} \cdot u_B^{V_{OC,m}} \quad (92)$$

- $u_{B,V_{OC}}^{\beta}$: uncertainty on V_{OC}^* due to the coefficient of variation of the voltage with the temperature.

$$u_{B,V_{OC}}^{\beta} = \frac{\partial V_{OC}^*}{\partial \beta} \cdot u_B^{\beta} = V_{OC,m} \cdot \frac{-(T_C - T_C^*)}{[1 + \beta(T_C - T_C^*)]^2} \cdot u_B^{\beta} \quad (93)$$

The Type B uncertainty on the extrapolated to STC voltage corresponds to:

$$u_B^{V_{OC}^*} = \sqrt{\left(\frac{\partial V_{OC}^*}{\partial T_C} \cdot u_B^{T_C(STC)}\right)^2 + \left(\frac{\partial V_{OC}^*}{\partial V_{OC,m}} \cdot u_B^{V_{OC,m}}\right)^2 + \left(\frac{\partial V_{OC}^*}{\partial \beta} \cdot u_B^{\beta}\right)^2} \quad (94)$$

$$u_B^{V_{OC}^*} = \sqrt{(0.345)^2 + (0.116)^2 + (0.028)^2} = 0.365\% \quad (95)$$

Power

For the calculation of the uncertainty on P_{MPP}^* , all sources of uncertainty which influence this parameter must be taken into account. In Figure 52 can be seen these sources and how they have been added to the uncertainty chain until reaching the final uncertainty.

Figure 52. Uncertainty sources and uncertainty chain on P_{MPP}^* .

The extrapolated to STC power is:

$$P_{MPP}^* = P_{MPP,m} \cdot \frac{G^*}{G_{ef}} \cdot \frac{1}{1 + \gamma(T_C - T_C^*)} \quad (96)$$

Applying the law of propagation of uncertainty:

- $u_{B,P_{MPP}^*}^{G_{ef}}$: uncertainty on P_{MPP}^* due to the irradiance.

$$u_{B,P_{MPP}^*}^{G_{ef}} = \frac{\partial P_{MPP}^*}{\partial G} \cdot u_B^{G_{ef}} = \frac{P_{MPP,m}}{1 + \gamma(T_C - T_C^*)} \cdot \frac{-1}{G_{ef}} \cdot u_B^{G_{ef}} \quad (97)$$

- $u_{B,P_{MPP}^*}^{T_C}$: uncertainty on P_{MPP}^* due to cell temperature.

$$u_{B,P_{MPP}^*}^{T_C} = \frac{\partial P_{MPP}^*}{\partial T_C} \cdot u_B^{T_C(STC)} = P_{MPP,m} \frac{-\gamma}{[1 + \gamma(T_C - T_C^*)]^2} \cdot u_B^{T_C(STC)} \quad (98)$$

- $u_{B,P_{MPP}^*}^{P_{MPP,m}}$: uncertainty on P_{MPP}^* due to the measured power.

$$u_{B,P_{MPP}^*}^{P_{MPP,m}} = \frac{\partial P_{MPP}^*}{\partial P_{MPP,m}} \cdot u_B^{P_{MPP,m}} = \frac{1}{1 + \gamma(T_C - T_C^*)} \cdot u_B^{P_{MPP,m}} \quad (99)$$

- $u_{B,P_{MPP}^*}^{\gamma}$: uncertainty on P_{MPP}^* due to the coefficient of variation of the power with the temperature.

$$u_{B,P_{MPP}^*}^{\gamma} = \frac{\partial P_{MPP}^*}{\partial \gamma} \cdot u_B^{\gamma} = P_{MPP,m} \frac{-(T_C - T_C^*)}{[1 + \gamma(T_C - T_C^*)]^2} \cdot u_B^{\gamma} \quad (100)$$

The Type B uncertainty on the extrapolated to STC power corresponds to:

$$u_B^{P_{MPP}^*} = \sqrt{\left(\frac{\partial P_{MPP}^*}{\partial G_{ef}} \cdot u_B^{G_{ef}}\right)^2 + \left(\frac{\partial P_{MPP}^*}{\partial T_C} \cdot u_B^{T_C(STC)}\right)^2 + \left(\frac{\partial P_{MPP}^*}{\partial P_{MPP,m}} \cdot u_B^{P_{MPP,m}}\right)^2 + \left(\frac{\partial P_{MPP}^*}{\partial \gamma} \cdot u_B^\gamma\right)^2} \quad (101)$$

$$u_B^{P_{MPP}^*} = \sqrt{(0.67)^2 + (0.464)^2 + (0.334)^2 + (0.041)^2} = 0.882\% \quad (102)$$

Fill Factor (FF)

The extrapolated to STC FF is:

$$FF^* = FF_m \cdot \frac{1}{1 + \delta(T_C - T_C^*)} \quad (103)$$

Applying the law of propagation of uncertainty:

- $u_{B,FF^*}^{T_C}$: uncertainty on FF^* due to cell temperature.

$$u_{B,FF^*}^{T_C} = \frac{\partial FF^*}{\partial T_C} \cdot u_B^{T_C(STC)} = FF_m \cdot \frac{-\delta}{[1 + \delta(T_C - T_C^*)]^2} \cdot u_B^{T_C(STC)} \quad (104)$$

- $u_{B,FF^*}^{FF_m}$: uncertainty on FF^* due to the measured FF .

$$u_{B,FF^*}^{FF_m} = \frac{\partial FF^*}{\partial FF_m} \cdot u_B^{FF_m} = \frac{1}{1 + \delta(T_C - T_C^*)} \cdot u_B^{FF_m} \quad (105)$$

- u_{B,FF^*}^δ : uncertainty on FF^* due to the coefficient of variation of the fill factor with the temperature.

$$u_{B,FF^*}^\delta = \frac{\partial FF^*}{\partial \delta} \cdot u_B^\delta = FF_m \cdot \frac{-(T_C - T_C^*)}{[1 + \delta(T_C - T_C^*)]^2} \cdot u_B^\delta \quad (106)$$

The Type B uncertainty on the extrapolated to STC fill factor corresponds to:

$$u_B^{FF^*} = \sqrt{\left(\frac{\partial FF^*}{\partial T_C} \cdot u_B^{T_C(STC)}\right)^2 + \left(\frac{\partial FF^*}{\partial FF_m} \cdot u_B^{FF_m}\right)^2 + \left(\frac{\partial FF^*}{\partial \delta} \cdot u_B^\delta\right)^2} \quad (107)$$

$$u_B^{FF^*} = \sqrt{(0.183)^2 + (0.334)^2 + (0.001)^2} = 0.381\% \quad (108)$$

Efficiency

The extrapolated to STC efficiency is:

$$\eta^* = \frac{P_{MPP}^*}{Area \cdot G^*} \quad (109)$$

Applying the law of propagation of uncertainty:

- $u_{B,\eta^*}^{G_{ef}}$: uncertainty on η^* due to the irradiance.

$$u_{B,\eta^*}^{G_{ef}} = \frac{\partial \eta^*}{\partial G_{ef}} \cdot u_B^{G_{ef}} = \frac{1}{Area \cdot G^*} \cdot \frac{P_{MPP}^*}{1 + \gamma(T_C - T_C^*)} \cdot \frac{-1}{G_{ef}} \cdot u_B^{G_{ef}} \quad (110)$$

- $u_{B,\eta^*}^{T_C}$: uncertainty on η^* due to cell temperature.

$$u_{B,\eta^*}^{T_C} = \frac{\partial \eta^*}{\partial T_C} \cdot u_B^{T_C(STC)} = \frac{1}{Area \cdot G^*} P_{MPP}^* \frac{-\gamma}{[1 + \gamma(T_C - T_C^*)]^2} \cdot u_B^{T_C(STC)} \quad (111)$$

- $u_{B,\eta^*}^{P_{MPP}^*}$: uncertainty on η^* due to the STC power.

$$u_{B,\eta^*}^{P_{MPP}^*} = \frac{\partial \eta^*}{\partial P_{MPP}^*} \cdot u_B^{P_{MPP}^*} = \frac{1}{Area \cdot G^*} \cdot \frac{1}{1 + \gamma(T_C - T_C^*)} \cdot u_B^{P_{MPP}^*} \quad (112)$$

- u_{B,η^*}^γ : uncertainty on η^* due to the coefficient of variation of the power with the temperature.

$$u_{B,\eta^*}^\gamma = \frac{\partial \eta^*}{\partial \gamma} \cdot u_B^\gamma = \frac{1}{Area \cdot G^*} P_{MPP}^* \frac{-(T_C - T_C^*)}{[1 + \gamma(T_C - T_C^*)]^2} \cdot u_B^\gamma \quad (113)$$

The Type B uncertainty on the extrapolated to STC efficiency corresponds to:

$$u_B^{\eta^*} = \sqrt{\left(\frac{\partial \eta^*}{\partial G_{ef}} \cdot u_B^{G_{ef}}\right)^2 + \left(\frac{\partial \eta^*}{\partial T_C} \cdot u_B^{T_C(STC)}\right)^2 + \left(\frac{\partial \eta^*}{\partial P_{MPP}^*} \cdot u_B^{P_{MPP}^*}\right)^2 + \left(\frac{\partial \eta^*}{\partial \gamma} \cdot u_B^\gamma\right)^2} \quad (114)$$

$$u_B^{\eta^*} = \sqrt{(0.67)^2 + (0.464)^2 + (0.888)^2 + (0.041)^2} = 1.206\% \quad (115)$$

COMBINED UNCERTAINTY

The combined uncertainty encompasses Type A and Type B uncertainties and is shown in the following table:

	P_{MPP}^* (%)	I_{SC}^* (%)	V_{OC}^* (%)	FF^* (%)	α (%/°C)	β (%/°C)	γ (%/°C)	η^* (%)
u_A	0.310	0.430	0.160	0.240	0.008 (13.33%)	0.010 (3.13%)	0.019 (4.41%)	0.100
u_B	0.882	0.742	0.365	0.381	0.013 (21.66%)	0.026 (8.13%)	0.038 (8.84%)	1.206
u_C	0.935	0.858	0.399	0.450	0.015 (25.43%)	0.028 (8.71%)	0.042 (9.88%)	1.210

Table 33. Combined uncertainties on the extrapolated to STC parameters and temperature coefficients.

EXPANDED UNCERTAINTY

The uncertainty is usually expressed with a 95% of confidence interval, which is equivalent to a coverage factor $k=2$. Once the uncertainties combined (Table 33) were obtained, these values should be multiplied by the coverage factor, obtaining:

$k=2$	P_{MPP}^* (%)	I_{SC}^* (%)	V_{OC}^* (%)	FF^* (%)	α (%/°C)	β (%/°C)	γ (%/°C)	η^* (%)
U	1.87	1.72	0.80	0.90	0.030 (50.86%)	0.056 (17.42%)	0.084 (19.76%)	2.42

Table 34. Expanded uncertainty with a confidence interval of 95% ($k=2$).

APPENDIX B. UNCERTAINTY TYPE A ON THE MEASUREMENTS OF PV MODULES

B.1 UNCERTAINTY TYPE A: MEASUREMENTS USING THE SOLAR BOX

As explained in section 3.3.4.1, a PV module has been characterized in the Solar Box for a whole year to quantify the Type A uncertainties on the electrical parameters and temperature coefficients. In Table 35, the average of the previous parameters and coefficients of the 15 measurements are presented:

P_{MPP}^* (W)	I_{MPP}^* (A)	V_{MPP}^* (V)	I_{SC}^* (A)	V_{OC}^* (V)	FF^*	α (%/°C)	β (%/°C)	γ (%/°C)
237.4	8.06	29.47	8.61	37.53	0.734	0.06	-0.32	-0.43

Table 35. Average of the characteristic parameters measured on a same PV module 15 times over a year.

The Type A expanded uncertainties ($U = \pm 2\sigma$), corresponding to each parameter, are shown in Table 36:

$U_A^{P_{MPP}^*}$ (%)	$U_A^{I_{MPP}^*}$ (%)	$U_A^{V_{MPP}^*}$ (%)	$U_A^{I_{SC}^*}$ (%)	$U_A^{V_{OC}^*}$ (%)	$U_A^{FF^*}$ (%)	U_A^α (%/°C)	U_A^β (%/°C)	U_A^γ (%/°C)
0.62	0.80	0.42	0.86	0.32	0.48	0.016 (26.66%)	0.020 (6.26%)	0.038 (8.81%)

Table 36. Type A expanded uncertainties ($k=2$) on the characteristic parameters measured on a same PV module 15 times over a year.

Figure 53 to Figure 61 show the time evolution of the electrical parameters and temperature coefficients of the tested module measured for a whole year. In these figures, individual values (blue diamonds), average value (red continuous line) and the expanded Type A uncertainty interval (orange dotted lines) are reported.

Figure 53. Expanded Type A uncertainty ($k=2$) on I_{sc}^* , measured 15 times during 2014. The blue diamonds represent the 15 measurements, the red continuous line is the average of the measurements of the I_{sc}^* , and the orange dotted lines report about the expanded Type A uncertainty.

Figure 54. Expanded Type A uncertainty ($k=2$) on V_{oc}^* , measured 15 times during 2014. The blue diamonds represent the 15 measurements, the red continuous line is the average of the measurements of the V_{oc}^* , and the orange dotted lines report about the expanded Type A uncertainty.

Figure 55. Expanded Type A uncertainty ($k=2$) on I_{MPP}^* , measured 15 times during 2014. The blue diamonds represent the 15 measurements, the red continuous line is the average of the measurements of the I_{MPP}^* , and the orange dotted lines report about the expanded Type A uncertainty.

Figure 56. Expanded Type A uncertainty ($k=2$) on V_{MPP}^* , measured 15 times during 2014. The blue diamonds represent the 15 measurements, the red continuous line is the average of the measurements of the V_{MPP}^* , and the orange dotted lines report about the expanded Type A uncertainty.

Figure 57. Expanded Type A uncertainty ($k=2$) on P_{MPP}^* , measured 15 times during 2014. The blue diamonds represent the 15 measurements, the red continuous line is the average of the measurements of the P_{MPP}^* , and the orange dotted lines report about the expanded Type A uncertainty.

Figure 58. Expanded Type A uncertainty ($k=2$) on FF^* , measured 15 times during 2014. The blue diamonds represent the 15 measurements, the red continuous line is the average of the measurements of the FF^* , and the orange dotted lines report about the expanded Type A uncertainty.

Figure 59. Expanded Type A uncertainty ($k=2$) on α_{isc} , measured 15 times during 2014. The blue diamonds represent the 15 measurements, the red continuous line is the average of the measurements of α_{isc} , and the orange dotted lines report about the expanded Type A uncertainty.

Figure 60. Expanded Type A uncertainty ($k=2$) on β_{voc} , measured 15 times during 2014. The blue diamonds represent the 15 measurements, the red continuous line is the average of the measurements of β_{voc} , and the orange dotted lines report about the expanded Type A uncertainty.

Figure 61. Expanded Type A uncertainty ($k=2$) on V_{Pmpp} , measured 15 times during 2014. The blue diamonds represent the 15 measurements, the red continuous line is the average of the measurements of V_{Pmpp} , and the orange dotted lines report about the expanded Type A uncertainty.

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Moretón R., Lorenzo E., Leloux J., **Carrillo J.M.** Visual Poster Presentation. *Dealing in practice with hot-spots*. 29th European Photovoltaic Solar Energy Conference and Exhibition. doi: 10.4229/EUPVSEC20142014-5BV.1.43. Amsterdam, Netherlands (September 2014).

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GLOSSARY

α	Coefficient of variation of the current with the temperature.
α_{Isc}	Coefficient of variation of the short-circuit current with the temperature.
a_n	Parameter for the adjustment of the variation of the efficiency of the PV module with the irradiance.
A	Amp.
AM	Air Mass.
β	Coefficient of variation of the voltage with the temperature.
β_{Voc}	Coefficient of variation of the open circuit voltage with the temperature.
B	Direct irradiance.
B_0	The solar constant (1367 W/m ²).
C	Coulomb.
°C	Celsius degree.
CdTe	Cadmium Telluride.
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas.
cm	Centimetre.
D	Diffuse irradiance.
δ	Coefficient of variation of the fill factor with the temperature.
D.A.S.	Data Acquisition System.
DC	Direct current.

D^C	Circumsolar diffuse irradiance.
D^I	Isotropic diffuse irradiance.
d_{RT}	Distance between the centres of the PV reference and tested modules.
ΔT_{RT}	Temperature difference between the centre of the reference and the tested modules.
ε_0	Eccentricity.
€	Euro.
η^*	PV module efficiency at STC.
$\eta_{0.2}$	PV module efficiency at 200 W/m ² and 25 °C.
$\eta_{0.6}$	PV module efficiency at 600 W/m ² and 25 °C.
$\eta(G_{ef}, T_C)$	PV module efficiency.
E.S.T.I.	European Solar Test Installation.
FF	Fill Factor.
FF^*	Fill Factor at STC.
FISE	Fraunhofer-ISE.
γ	Coefficient of variation of the power with the temperature.
G	Global irradiance.
G^*	Global irradiance at STC.
G_{ef}	Effective global irradiance that effectively contributes to the generation of electricity.
<i>GS-IES-UPM</i> Research group of PV systems of the Instituto de Energía Solar of the Universidad Politécnica de Madrid.	

GW	Gigawatt.
GW _p	Gigawatt-peak.
<i>I</i>	Current.
IEC	International Electrotechnical Commission.
IGBT	Insulated Gate Bipolar Transistor.
<i>I</i> _{MPP}	Current at the maximum power point.
<i>I</i> _{MPP} [*]	Current at the maximum power point at STC.
IR	Infrared.
<i>I</i> _{SC}	Short-circuit current.
<i>I</i> _{SC} [*]	Short-circuit current at STC.
<i>I</i> _{SC,m}	Measured short-circuit current.
<i>I-V</i>	Characteristic curve of a PV module or array.
<i>k</i>	Boltzmann constant ($k = 1,38 \cdot 10^{-23}$ J/K).
<i>k</i>	Coverage factor.
K	Kelvin.
kΩ	Kilo-ohm.
kW	Kilowatt.
kW/m ²	Kilowatt per square metre.
LCOE	Levelized Cost of Energy.
LID	Light Induced Degradation.
Ln	Neperian logarithm.

m	Diode ideality factor ($m = 1.3$).
m	Metre.
m^2	Square metre.
MBE	Mean Bias Error.
μF	Microfarad.
mF	Milifarad.
$m\Omega$	Miliohmium.
ms	Milisecond.
MS/s	Megasample per second.
mV	Milivolt.
MW	Megawatt.
MWh	Megawatt-hour.
MW_p	Megawatt-peak.
NOCT	Nominal Operation Cell Temperature.
N_S	Number of cells in series in a PV module.
Ω	Ohm.
PC	Personal computer.
P_{DC}	Continuous power delivered by the PV array.
P_{MPP}	Maximum power of a PV generator.
P_{MPP}^*	Maximum power of a PV generator at STC.
$P_{MPP,m}$	Measured maximum power of a PV generator.

$P_{MPP,REF,m}^*$	Measured maximum power extrapolated to STC (reference module).
$P_{MPP,REF,CAL}^*$	Calibration value of the maximum power at STC (reference module).
$P_{MPP,TEST,ASSIGNED}^*$	Assigned STC power to the tested module.
$P_{MPP,TEST,m}^*$	Measured maximum power extrapolated to STC (tested module).
PR	Performance Ratio.
PV	Photovoltaic.
q	Elemental charge ($q = 1.602 \cdot 10^{-19}$ C).
QAP	Quality Assurance Procedure.
RMSE	Root Mean Square Error.
Shunt	Calibrated resistor with very low resistance and high accuracy.
S.I.	International System of Units.
σ	Standard deviation.
STC	Standard Test Conditions.
T_A	Ambient temperature.
t_C	Charging time.
T_C	Cell temperature.
T_C^*	Cell temperature at STC.
$T_{C,REF}$	Cell temperature of the reference module.
$T_{C,TEST}$	Cell temperature of the tested module.
T_{REF}	Temperature of the reference module measured with a commercial sensor.
T_{TEST}	Temperature of the tested module measured with a commercial sensor.

θ_S	Incident angle.
u_A	Type A uncertainty.
u_A^α	Type A uncertainty on the temperature coefficient of the current.
u_A^β	Type A uncertainty on the temperature coefficient of the voltage.
u_A^γ	Type A uncertainty on the temperature coefficient of the power.
$u_A^{\eta_{0.6}}$	Type A uncertainty on the PV module efficiency at 600 W/m ² .
$u_A^{\eta_{0.2}}$	Type A uncertainty on the PV module efficiency at 200 W/m ² .
$u_A^{FF^*}$	Type A uncertainty on the fill factor at STC.
$u_A^{I_{MPP}^*}$	Type A uncertainty on the current at the maximum power point at STC.
$u_A^{I_{SC}^*}$	Type A uncertainty on the short-circuit current at STC.
$u_A^{P_{MPP}^*}$	Type A uncertainty on the maximum power at STC.
$u_A^{V_{MPP}^*}$	Type A uncertainty on the voltage at the maximum power point voltage at STC.
$u_A^{V_{OC}^*}$	Type A uncertainty on the open circuit voltage at STC.
u_B	Type B uncertainty.
u_B^{RCC}	Type B uncertainty of the calibration value on the short-circuit current of the reference cell.
$u_B^{Dat,Res}$	Type B uncertainty due to the resolution of the datalogger (analog/digital conversion - 20 bits).
$u_B^{Dat,Acc}$	Type B uncertainty due to the accuracy of the datalogger.
u_B^{Gef}	Type B uncertainty on the effective irradiance.

- u_B^{PT1000} Type B uncertainty due to the accuracy of PT1000 sensors.
- $u_B^{PT1000(STC)}$ Type B uncertainty due to the accuracy of PT1000 sensors at STC.
- $u_B^{PT1000(50^{\circ}C)}$ Type B uncertainty due to the accuracy of PT1000 sensors at 50 °C.
- $u_B^{\Delta T3}, u_B^{\Delta T7}$ Type B uncertainties in the non-uniformity of temperature on the surface of the PV module (at STC and other than STC, respectively).
- u_B^{BTC} Type B uncertainty due to backskin to cell thermal drop.
- $u_B^{Dat,Res}$ Type B uncertainty due to the resolution of the datalogger (analog/digital conversion - 20 bits).
- $u_B^{Dat,Acc}$ Type B uncertainty due to the accuracy of the datalogger.
- $u_B^{Tc(STC)}$ Type B uncertainty on the cell temperature at STC.
- $u_B^{Tc(50^{\circ}C)}$ Type B uncertainty on the cell temperature at 50 °C.
- $u_B^{Osc,Res}$ Type B uncertainty due to oscilloscope resolution (analog/digital conversion - 12 bits).
- $u_B^{Osc,Acc}$ Type B uncertainty due to the accuracy of the oscilloscope.
- u_B^{Res} Type B uncertainty due to the calibrated resistor used for current measurement.
- $u_B^{Isc,m}$ Type B uncertainty on the measured short-circuit current.
- $u_B^{Voc,m}$ Type B uncertainty on the measured open circuit voltage.
- $u_B^{P_{MPP},m}$ Type B uncertainty on the measured maximum power.
- u_B^{α} Type B uncertainty on the temperature coefficient of the current.
- u_B^{β} Type B uncertainty on the temperature coefficient of the voltage.

u_B^γ	Type B uncertainty on the temperature coefficient of the power.
$u_{B,I_{SC}^*}^{G_{ef}}$	Type B uncertainty due to the effective irradiance on the short-circuit current at STC.
$u_{B,I_{SC}^*}^{T_C}$	Type B uncertainty due to cell temperature on the short-circuit current at STC.
$u_{B,I_{SC}^*}^{I_{SC,m}}$	Type B uncertainty due to the measured current on the short-circuit current at STC.
$u_{B,I_{SC}^*}^\alpha$	Type B uncertainty due to the temperature coefficient of the current on the short-circuit current at STC.
$u_B^{I_{SC}^*}$	Type B uncertainty on the short-circuit current at STC.
$u_{B,V_{OC}^*}^{T_C}$	Type B uncertainty due to cell temperature on the open circuit voltage at STC.
$u_{B,V_{OC}^*}^{V_{OC,m}}$	Type B uncertainty due to the measured voltage on the open circuit voltage at STC.
$u_{B,V_{OC}^*}^\beta$	Type B uncertainty due to the temperature coefficient of the voltage on the open circuit voltage at STC.
$u_B^{V_{OC}^*}$	Type B uncertainty on the open circuit voltage at STC.
$u_{B,P_{MPP}^*}^{G_{ef}}$	Type B uncertainty due to the effective irradiance on the maximum power at STC.
$u_{B,P_{MPP}^*}^{T_C}$	Type B uncertainty due to cell temperature on the maximum power at STC.
$u_{B,P_{MPP}^*}^{P_{MPP,m}}$	Type B uncertainty due to the measured power on the maximum power at STC.

$u_{B,P_{MPP}}^{\gamma}$	Type B uncertainty due to the temperature coefficient of the power on the maximum power at STC.
$u_B^{P_{MPP}^*}$	Type B uncertainty on the maximum power at STC.
$u_{B,FF}^{T_C}$	Type B uncertainty due to cell temperature on the fill factor at STC.
$u_{B,FF}^{FF_m}$	Type B uncertainty due to the measured fill factor on the fill factor at STC.
$u_{B,FF}^{\delta}$	Type B uncertainty due to the temperature coefficient of the fill factor on the fill factor at STC.
$u_B^{FF^*}$	Type B uncertainty on the fill factor at STC.
$u_{B,\eta}^{G_{ef}}$	Type B uncertainty due to the effective irradiance on the PV module efficiency at STC.
$u_{B,\eta}^{T_C}$	Type B uncertainty due to cell temperature on the PV module efficiency at STC.
$u_{B,\eta}^{P_{MPP}^*}$	Type B uncertainty due to the STC power on the PV module efficiency at STC.
$u_{B,\eta}^{\gamma}$	Type B uncertainty due to the temperature coefficient of the power on the PV module efficiency at STC.
$u_B^{\eta^*}$	Type B uncertainty on the PV module efficiency at STC.
u_C	Combined uncertainty.
u_C^{α}	Combined uncertainty on the temperature coefficient of the current.
u_C^{β}	Combined uncertainty on the temperature coefficient of the voltage.
u_C^{γ}	Combined uncertainty on the temperature coefficient of the power.

$u_c^{\eta'}$	Combined uncertainty on the PV module efficiency.
u_c^{FF*}	Combined uncertainty on the fill factor at STC.
$u_c^{I_{SC}^*}$	Combined uncertainty on the short-circuit current at STC.
$u_c^{P_{MPP}^*}$	Combined uncertainty on the maximum power at STC.
$u_c^{V_{OC}^*}$	Combined uncertainty on the open circuit voltage at STC.
USB	Universal Serial Bus.
V	Volt.
V	Voltage.
V_{MPP}	Voltage at the maximum power point.
V_{MPP}^*	Voltage at the maximum power point at STC.
V_{OC}	Open circuit voltage.
V_{OC}^*	Open circuit voltage at STC.
V_{OC}^C	Open circuit voltage corrected in irradiance.
$V_{OC,m}$	Measured open circuit voltage.
W	Watt.
Wh	Watt-hour.
W/m ²	Watt per square metre.
W _p	Watt-peak.

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