

Uncertainty calculation of indoor and outdoor performance measurements for PV modules

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Abstract. Since uncertainties are often overlooked, this analysis highlights why considering uncertainties on PV power or efficiency values is crucial in order to compare published values for different PV technologies. Following the International Energy Agency Report on “Uncertainties in PV System Yield predictions and Assessments” and European FP7 Sophia project, the state of the art of outdoor and indoor uncertainty calculations on PV modules performances is reviewed. Calculation tools are compared and discussed in order to identify the most relevant one. Indoor measurements are based on instantaneous measurements with a dedicated set up: a solar simulator, called “flash-test”. The simulated conditions are close to the standard tests conditions with a stable irradiance, AMG1.5 spectrum and at $25\text{ °C} \pm 1\text{ °C}$, which are more stable than outdoor tests. Outdoor measurements are taken performed on variable time periods. Variations over months are commonly observed within $\pm 5\%$ that is why averaging on long periods looks relevant to reduce the standard deviation down to 1.3% . Outdoor measurements are performed close to Chambéry in France, under a soft alpine climate, with current-voltage curve tracers. Indoor and outdoor values are finally compared and discussed.

1 Introduction

Uncertainty calculations on PV modules characteristics have been widely described for indoor measurements in 2007 by the Joint Research Center (JRC) [1] and in 2013 by Dirnberger et al. [2] from the FhG Institute (FhG). All inputs for uncertainty evaluation tables have been detailed in the European and International norms ([3] to [14]) which pinpointed the need of calibration traceability [7]. In 2018, an inter-comparison work [15] underlined that nine laboratories took various inputs as contributions to the overall STC power uncertainty measurements. The resulting uncertainty varied from 1.6% to 5.1% depending on the technology under consideration. The main inputs differences come from the following items:

- The reference device calibration (below 1% uncertainty for the reference cell and around 2% for the reference module);
- The spatial non uniformity of the irradiance (from 0.1% up to almost 3% , depending on the set up);
- The spectral mismatch factor (from 0.1% to almost 2% depending on the module technology);
- The characteristics of the capacitive module effect (from 0.1% to 0.7%).

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In order to harmonize the uncertainty calculations of indoor power measurements over all the laboratories, a tool created by the JRC for the EC Integrated Project Performance has been proposed in 2007 [1]. Then, in 2013, Dirnberger et al. proposed an improved uncertainties calculation focused on crystalline Si and thin-film modules calibration [2]. Those proposals could have enabled systematic uncertainty comparison between different laboratories. However this practice seems to be hardly widespread. In addition, fewer works have been reported on outdoor PV measurement uncertainties compared to indoor ones.

In this paper, the uncertainty calculation background is first recalled to support the analysis of the effect of the combination of the different uncertainty contributions. After that, the uncertainty contributions are compared between the tools proposed by JRC and FhG. The effect of the inputs choice and the measurement set up on the uncertainties level is evaluated. Based on that, we report on the results of a new statistical tool for the uncertainty calculations of outdoor PV electrical characteristics. Finally, the outputs of this tool are compared to statistics of outdoor measurements. Indoor STC measurements and manufacturer data are compared to outdoors ones.

2 Uncertainty calculation background

“Uncertainty estimation are based on paragraphs 5.1.4 and 5.1.5 of GUM” [16]. “The uncertainty measurement equation gives how a small change δ_i in the input quantity X_i propagates to the output quantity Y through the following relation:

$$Y = Y_0 + c_1 \delta_1 + c_2 \delta_2 + \dots + c_n \delta_n \quad (1)$$

with, Y the measurand, X_i the input quantities, $Y_0 = f(X_{1,0}, X_{2,0}, \dots, X_{n,0})$ and $X_{1,0}, X_{2,0}, \dots, X_{n,0}$ the nominal values, $\delta_i = X_i - X_{i,0}$ the transformations of the input quantities and c_i the sensitivity coefficients. All uncertainties given in tables in this article are relative standard uncertainties. Standard uncertainty of a rectangular probability distribution with half width Ω is $\Omega/\sqrt{3}$. Half width of a rectangular probability distribution is indicated “ \pm ” in the text. A combined uncertainty u_c of the measurand y is calculated according to the law of propagation of uncertainty as follows:

$$u_c^2(y) = (c_1 u_{X1})^2 + (c_2 u_{X2})^2 + \dots + (c_n u_{Xn})^2 \quad (2)$$

where, u_{X_i} is the uncertainty of the measurand X_i and c_i the corresponding sensitivity coefficient.

Expanded uncertainty of all electrical parameters of the module is calculated with a coverage factor $k = 2$ to obtain 95 % coverage interval” of a Gaussian distribution. “As a significant number of input quantities with normal and rectangular distributions is involved, the probability distribution of the measurements is considered to be normal.”[2]

3 Indoor STC power uncertainties of PV modules

In this section, we analyse the uncertainty calculation results for the PV module characteristics using different tools of calculation.

3.1 Sensitivity of JRC tool to the inputs selection

JRC tool takes into account the different inputs to calculate the uncertainty combinations for each electrical characteristic to determine the uncertainty on the power of the module.

Among the different inputs are:

- Uncertainty on calibration of the reference cell

- Thermal sensitivity coefficients on V, I and irradiance
- Uncertainties related to the orientation of the panel with respect to the light source
- Measurement uncertainty of I, V, Irradiance but under a single parameter called "data acquisition error" fixed at an arbitrarily estimated value to cover all the contributions of the 3 measured quantities.

The error on the measurements is actually of 2 types:

- Intrinsic uncertainty of the measuring instrument from manufacturer data (Data sheet)
- Experimental uncertainty related to the reproducibility of the equipment on the one hand and to the operator on the other

The parameter introduced in the JRC calculation should cover the combination of these 2 types of contribution. In our set-up, the operator's reproducibility is predominant, 0.24 % while the equipment's reproducibility is 0.04 %. Therefore, the value of the global parameter "data acquisition error" set at 0.2 % would underestimate the contribution of measurement errors. To reduce the impact of measurement errors, action should be taken on operator reproducibility.

As far as temperature effects are concerned, the sensitivity coefficients of the measurements are specific to the type of technology of the modules. The JRC tool considers that measurements are performed under a temperature stability condition of ± 1 °C. In this case, the impact of the value of these coefficients on the uncertainty calculation is negligible. However, if stability conditions are less favourable, the impact can become significant. Thus, in the case of a degraded stability at ± 2.5 °C, the power uncertainty can be increased by 0.5 %.

After reviewing JRC tool, it would be interesting to compare it to FhG tool.

3.2 Comparison between JRC with FhG tools

The goal of FhG tool is to reduce the measurement uncertainty for crystalline silicon (c-Si) and thin film power module. For this purpose, the sources of uncertainties related to their measurement bench and measurement protocol are specified. The main contributions of the uncertainties are split into three different tables: one concerning the effective irradiance; one concerning the temperature; one concerning the I-V curve parameters for c-Si modules. Then, a summary table allows to calculate the combination of the different uncertainty contributions of each electrical parameter. Finally, an overview table compares these expanded uncertainties for the different technologies: "crystalline silicon (Si-c) standard", "cadmiumtelluride", "typical amorphous silicon (Pn junction)", "CI(G)S".

In comparison with the JRC tool, the same STC power uncertainty of 1.6 % for the Si-C module was calculated with slightly different contributions (Table 1). The calibration of the reference device and the uncertainty of the mismatch spectral correction, both considered by FhG, are slightly higher than those of JRC. These contributions might be compensated, among other ones, by a lower considered "data acquisition error" than JRC did...

Table 1. Results of some uncertainty estimations comparison for Si-c module

Institute	Data acquisition error	Calibration of reference device (k = 2)	Uncertainty of spectral mismatch correction (k = 2)	STC power uncertainty
FhG	$\pm 0.164 \text{ }^{\circ}\text{C}$ (k = 2)	0.6 %	0.84 %	1.6 %
JRC	$\pm 0.2 \text{ }^{\circ}\text{C}$ (k = 2.586)	0.5 %	0.54 %	1.6 %

To conclude, both FhG and JRC tools enable to get the same result for STC power uncertainty of Si-c technology module.

Based on this work, it would have been interesting to measure the impact of:

- The variation in the size of a module on the uncertainties of the effective irradiance and the efficiency of the module; indeed, the size of their module can be "up to 2.2 m x 1.1 m".
- The nature of the back of the panel or the nature of the anti-reflection layers on the uncertainty of the effective irradiance
- Taking into account the drift of the temperature sensor in the contribution on temperature uncertainty.

On the one hand, we have introduced corrections in the tool proposed by FhG to calculate the uncertainties to circumvent these limits. But we found no significant effect below the 15.6 cm x 15.6 cm threshold values for cell size, which would then contribute 0.1 % to the standard surface uncertainty and 2 % to the temperature sensor drift.

On the other hand, the checks of the power delivered by the reference panel can be carried out several days apart. In this case, a maximum drift threshold on the value of this power is used in the uncertainty calculation. The calibration is renewed by an electronic correction when this threshold is reached. This drift threshold is defined at an acceptable value of 0.2 %.

After reviewing indoor uncertainties calculations, a specific tool for outdoor uncertainties calculations is proposed in the following paragraph, as we found out it was a scarce but much needed information.

4 Outdoor uncertainties calculations of PV module performance

Here a user-friendly calculation tool is proposed. The equations will be introduced before explaining the tool.

4.1 Electrical characteristics uncertainties

As hypothesis, all variables are independents.

4.1.1. Current uncertainty calculations

Current uncertainty has been obtained through derived equations considering voltage and resistance uncertainties, depending on automatically selected calibers.

4.1.2. Fill factor (FF) uncertainty calculations

$$FF = \frac{V_M \cdot I_M}{V_{CO} \cdot I_{CC}} \quad (3)$$

$$\left(\frac{U_{FF}}{FF}\right)^2 = \left(\frac{U_{V_M}}{V_M}\right)^2 + \left(\frac{U_{I_M}}{I_M}\right)^2 + \left(\frac{U_{I_{CC}}}{I_{CC}}\right)^2 + \left(\frac{U_{V_{CO}}}{V_{CO}}\right)^2 \quad (4)$$

With FF fill factor, I_M , V_M : current, voltage at maximum power, I_{CC} : short circuit current, V_{CO} : open circuit voltage.

NB: experimental relative standard deviation of mean FF over one year is added to combined uncertainty.

4.1.3. Irradiance uncertainty calculation

$$I_r = U_{mes} \times C_{ir} \quad (5)$$

With I_r irradiance, U_{mes} is voltage measured by reference panel for an irradiance of around 1000 W/m², C_{ir} irradiance variation coefficient in W/m²/V.

NB: three other contributions have been considered:

- Spectral response variation coefficient between sun spectrum and AMG1.5 and between reference cell and characterized module spectral response. We make the hypothesis this contribution is included into spectral mismatch factor of 0.3 % (value given by FhG certificate for crystalline silicon as characterized module is crystalline silicon too)
- Drift coefficient: ageing drift of reference cell crystalline silicon sensor
- Cell temperature coefficient taking into account cell thermal sensitivity, where reference cell temperature T_j and a coefficient T_{coef} of short circuit current temperature normalized to short circuit current at 25 °C in 1 / °C is considered [7]:

$$f(T_j) = \frac{1}{1 - T_{coef} * (25^\circ C - T_j)} \quad (6)$$

We obtain irradiance uncertainty UI_r (5) considering uncertainties combination of:

- Relative voltage error measured by reference panel for an irradiance of around 1000 W/m² (depending on manufacturer datasheet uncertainty)

- FhG certificate error of output voltage at STC

NB: both are given for coverage factor $k = 2$.

- Drift, spectral mismatch factor and temperature contribution are added to irradiance uncertainty combination calculation with a rectangular distribution. Temperature contribution is given by maximum value between calculated coefficients ΔC_{temp_x} with T_x being minimum reference cell temperature and then maximum reference cell temperature:

$$\Delta C_{temp_x} = f(T_x + EMT) - f(T_x) \quad (7)$$

where EMT is reference cell thermal sensor uncertainty in Celsius degree.

4.1.4. Module efficiency uncertainty calculations

The module efficiency η is given by:

$$\eta = \frac{V_M \cdot I_M}{S \cdot I_r} \quad (8)$$

Where V_M , I_M are current, voltage at maximum power, S surface of the module and I_r irradiance on reference cell for about 1000 W/m². Efficiency uncertainty is given by:

$$\left(\frac{u_\eta}{\eta}\right)^2 = \left(\frac{u_{V_M}}{V_M}\right)^2 + \left(\frac{u_{I_M}}{I_M}\right)^2 + \left(\frac{u_S}{S}\right)^2 + \left(\frac{u_{I_r}}{I_r}\right)^2 \quad (9)$$

These additional contributions were considered:

- Experimental standard deviation divided by the mean value, which needs to be defined over a certain period of time
- A temperature coefficient with a rectangular distribution, which is the module temperature coefficient obtained by (7) calculations, with the temperature coefficient of the module instead of the reference cell's one.

Uncertainty of surface module u_S depends on relative uncertainties of the length L and the width l :

$$\left(\frac{u_S}{S}\right)^2 = \left(\frac{u_l}{l}\right)^2 + \left(\frac{u_L}{L}\right)^2 \quad (10)$$

The choice of panel refers to a selection of different sizes of modules, influencing surface uncertainty.

4.1.5. Power uncertainty calculations

Raw delivered power P is current multiplied by voltage at maximum power.

It is corrected by temperature coefficient of power module to get temperature corrected power P_{corr} . In addition, reference cell irradiance I_r is corrected by temperature coefficient of irradiance reference cell with formula (7) to obtain corrected reference cell irradiance I_{rcorr} . Then, "SIT corrected power" or "SIT P " is the temperature corrected power of module multiplied by 1000 W/m² divided by corrected reference cell irradiance I_{rcorr} .

$$SIT \text{ corrected Power} = \frac{P_{corr} \times 1000}{I_{rcorr}} \quad (11)$$

The uncertainty of the raw power of module is:

$$\left(\frac{u_P}{P}\right)^2 = \left(\frac{u_{V_M}}{V_M}\right)^2 + \left(\frac{u_{I_M}}{I_M}\right)^2 \quad (12)$$

Thus, the uncertainty of SIT corrected power depends of raw power of module and irradiance uncertainties and temperature variations of reference cell and measured module obtained by (7) formula, with a rectangular distribution. Experimental relative standard uncertainty was

also added, which needs to be defined over a certain period of time: over a day: 5 %, over a month: 3 % or over a year: 1.3 %.

4.2 CEA outdoor uncertainties tool

Here is presented an uncertainty evaluation tool of outdoor module electrical characteristics measurements, achieved with the collaboration of CETIAT (Fig.1). Hypothesis, experimental data inputs, parameters, results calculation, absolute and relative expanded uncertainties and a useful notice are disclosed in this one-page tool.

1 Hypotheses		Outdoor			
25 Experimental data			Notice		
36 V _m		50,0	V	1. Fill V _{co} , I _{cc} , target irradiance and V irradiance's measured voltage	
37 V _{cc}		60,0	V	Choose 15.8 x 15.8 cm ² "cell" or 1.5 x 1.5 m ² "panel 1"; Module sensibility is 0.45 %/K and reference cell sensibility is 0.06 %/K	
38 Inputs I _m		6,0	A	Experimental standard deviation: 0.05 % for FF and 1 % for power efficiency; Measuring calibre for resistance and multimeters are chosen automatically. Minimum and maximum temperatures : 10 °C and 55 °C for the module and 0 °C and 45 °C for the reference cell	
39 I _{cc}		8,0	A	2. FF, efficiency and power are calculated for a specific irradiance around 1000 W/m ²	
40 choice of panel		cell		3. Expanded uncertainty is column C and relative ones in column F	
49 Parameters to be modified		Parameters			
50 Light capture					
Unscrolled List		Measured voltage on reference V for an irradiance around 1000 W/m ²		Information:	
55		0,03350	V	32.23 mV < reference 1 < 33.89 mV	
61 Module dimension				32.21 mV < reference 2 < 33.87 mV	
65 Thermal parameter of the climatic container including airconditioning (stable around 25 °C)				32.16 mV < reference 3 < 33.8 mV	
66 Module thermal parameters					
73 Reference cell thermal parameters					
74 Calculations for 1000 W/m ²		FF	0,63		
80 Results		I _{m,module}	12,4		
		P	300	W	
		SIT corrected P = "SIT P"	221	W	
83 Expanded uncertainties U _x				Relativ expanded uncertainties U _x /x	
85 k=2	U _{Vcc}	3,47E-03	V	U _{Vcc} /Vcc	0,01%
89 k=2	U _{Icc}	4,22E-02	A	U _{Icc} /Icc	0,53%
902 k=2	U _{module efficiency}	0,49		U _{efficiency} /efficiency	3,9%
904 k=2	U _P	55,8	W	U _P /P	18,6%
905 k=2	U _{SIT P}	11,8	W	U _{SIT P} /SIT P	3,9%

Fig. 1. Proposed tool for outdoor uncertainty calculations

To begin with, we integrated a short notice (line 35 to 40; column E-F) which explains how to properly use our tool.

In order to gain space, the hypotheses are hidden (line 1 to 35), still they can be unscrolled if needed. As for important set up data – related to the type and size of module and their technical characteristics – as well as experimental results on standard deviation on FF or power, they are disclosed so that users are informed of the set up tool parameters. The “choice of panel” (line 40) is a multi-choice list that enables users to choose the proper size of their measured module, thus impacting the surface’s uncertainty. In the parameters’ part, users can easily scroll or unscroll any list to modify the tool so that it fits their needs; the information given on the certified voltage regarding the three reference devices for an irradiance of 1000 W/m² (line 55 column E) correspond to the authorized interval measures depending on the chosen reference (see paragraph 4.3 for details). Results (lines 79 to 82) and absolute and relative expanded uncertainties (lines 83 to 105) are automatically calculated (according to the formulas in previous paragraph).

4.3 Details of the model

Concerning hypotheses, the main point is that all variables are supposed to be independent. Moreover, an air conditioning system allows to stabilize bungalow temperature, where all temperature sensitive specified electronics are located.

Figure 2 show the operation spirit of the scrolling parameter parts for light capture parameters as an example.

49	Parameters to be modified			
50	Light capture			
51	Uncertainty Pyranometer (irradiance)	including 0.2% related to tilt and orientation errors	2	% for k = 2
52	Irradiance measure from one of the three module's references certified by Fraunhofer			
53	Cir		29851	W / m ² / V
54	Ir Light Power		1000	W / m ²
55		Measured voltage on reference V for an irradiance around 1000 W/m ²	0,03350	V
56		Uncertainty on reference's voltage for 1000 W/m ² irradiance (Fraunhofer's certificate)	2,5	% for k = 2
57		Silicon Crystalline detector Ageing Drift Spectral mismatch between AM1.5 G and real spectrum : taken into account into Fraunhofer's certificate : 0.3%	1	%
58		Error related to the various reflexion between reference cell and panel to be measured : depending on anti-reflexion surface layer	0,3	%
59		Tilt error between reference cell and measured panel is negligible: both on same structure with same slope	0,1	%
60			0,1	%

Information:
 32.23 mV < reference 1 < 33.89 mV
 32.21 mV < reference 2 < 33.87 mV
 32.16 mV < reference 3 < 33.8 mV

Fig. 2. Given details of the uncertainty evaluation tool

Shunt and multimeters range is automatically selected while filling open circuit voltage V_{oc} and short circuit current I_{cc} (line 44 to 48). Technical data given by manufacturer datasheet will define their electrical values uncertainty formula.

Experimental standard deviation of Form Factor FF , Raw Power P and STC Corrected Power $SIT P$ are disclosed line 41 and 43.

Module and reference cell thermal parameter list includes for example their sensibility, minimum and maximum temperatures, and maximum permitted variation related to temperature sensor.

What could be highlighted from this presented model is the user-friendly approach. Allowing users to easily modify the uncertainty calculation model gives more confidence in the results and thus in the entire chain of measure.

Now, to underline our hypothesis, this simplified model will be applied to experimental measures.

5 Outdoor power uncertainties and indoor correlations

In this part, we will first discuss outdoor raw measures; then, corrected measures will be presented. Finally, they will be compared to STC indoor power uncertainty measure and the manufacturer's one.

5.1 Outdoor raw measures

The poly-crystalline module is facing south, fixed tilt is 25 ° towards the ground and the thermocouple is glued in the middle of the rear side. Current-Voltage (I-V) curves are taken every 5 minutes when the reference cell irradiance is in the range 980 to 1020 W/m².

Figure 3 shows outdoor module raw power statistics over three years and reference cell and module temperatures, as well as the number of measurements for each day.

The number of measurements varies every day according to the weather (from 1 to 26 points per day). Consequently, standard deviation per day should be considered with caution.

Mean temperatures of reference cell and module have been represented to pinpoint inverted correlation between their variations and mean delivered power measures.

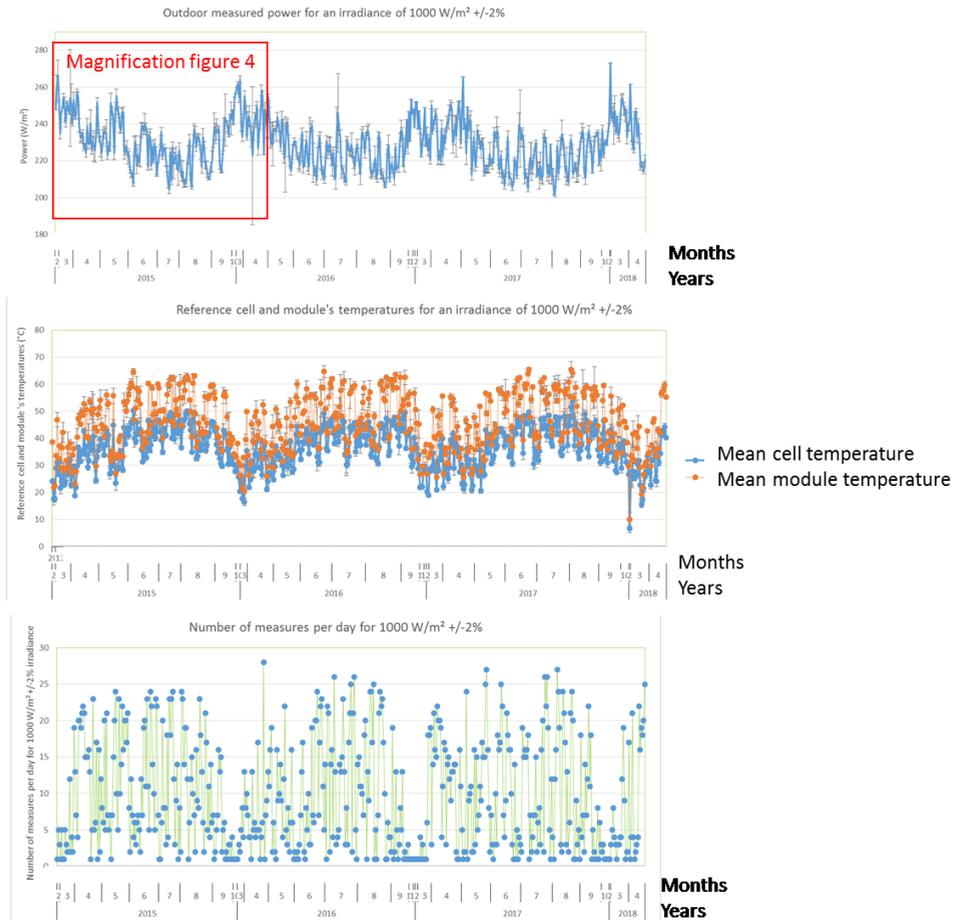


Fig. 3. Outdoor module delivered power statistics over three years and reference cell and module temperatures

Within a day, within hours, temperature can drop maximum 20 °C according to the weather. The hotter, the less mean delivered power, with a maximum power reduction of 23 %. The mean temperature of the reference cell is lower than the mean temperature of the module because of their area difference. The bigger module area, the hotter the module is.

The mean delivered raw power drift is neglected over 3 years and a half.

5.2 Outdoor corrected measures: comparison

SIT corrected power is calculated from equation 11 in order to be able to compare module output power for a specific irradiance of 1000 W/m² and for a “stable” temperature.

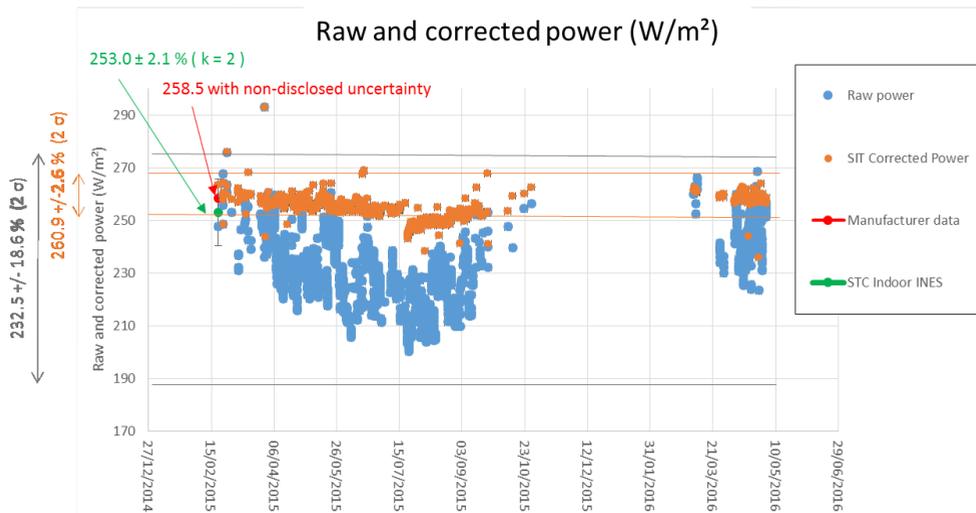


Fig. 4. Outdoor indoor uncertainties comparison of PV module power (expanded area from Fig. 3)

For an irradiance between 980 and 1020 W/m^2 , the mean raw power delivered by the module over three years is $232.5 \pm 18.6\%$ W/m^2 (measured for specific temperatures from minimum 20 °C to maximum 66 °C). Expanded experimental uncertainties represented on figure 4 is two standard deviation σ . Being the main contribution, our tool gives a global extended raw power uncertainty of the same amount.

As for an irradiance of the exact value of 1000 W/m^2 , the mean SIT corrected power towards temperature and irradiance is $260.9 \pm 2.6\%$ W/m^2 over one year and two months. Our tool gives a calculated global expanded uncertainties of SIT corrected power of 3.9 %, considering 1.3 % as experimental SIT corrected power standard deviation (for $k = 1$), raw power and irradiance uncertainties and temperature variations for reference cell and module.

Thus, our tool is now confirmed to be realistic.

STC Indoor Measure at INES was measured at $253 \pm 2.1\%$ W/m^2 and STC Manufacturer power is given to 258.5 W/m^2 with non-disclosed uncertainty. Both values are included in mean corrected power and mean raw power and their expanded experimental uncertainties. This comparison strengthens the confidence we have in our measures but mostly in our indoor and outdoor tools.

6 Conclusion

Uncertainties are often overlooked. This analysis allowed us to highlight why considering uncertainties on PV power or efficiency values is crucial in order to compare published values for different PV technologies. Studying indoor FhG and JRC STC power uncertainty calculation tools enables us to master our own uncertainties calculations taking into account a specific set up. Various inputs as calibration reference device uncertainty, spectral mismatch correction, and temperature variation from 25 °C during measurement, have greatest impact on global power uncertainty. Influenced by these analyses, the CEA outdoor global power uncertainty tool has been designed with a specification to be user-friendly and ergonomic; it enables users to adapt their uncertainty calculation to various set up and module technology. Outdoor raw and corrected measures confirmed the confidence of our model and of our uncertainty calculations. As for our prospect, by using the new World PV Scale Standard (WPVS) reference cell in CEA's flash test set up – from 0.5 % instead of our previous values of 2 % – our STC global power uncertainty will be dramatically reduced.

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