BANKABLE PROCEDURES FOR THE TECHNICAL QUALITY ASSURANCE OF LARGE SCALE PV PLANTS

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ABSTRACT: Strict technical quality assurance procedures are essential for PV plant bankability. When large-scale PV plants are concerned, this is typically accomplished in three consecutive phases: an energy yield forecast, that is performed at the beginning of the project and is typically accomplished by means of a simulation exercise performed with dedicated software; a reception test campaign, that is performed at the end of the commissioning and consists of a set of tests for determining the efficiency and the reliability of the PV plant devices; and a performance analysis of the first years of operation, that consists in comparing the real energy production with the one calculated from the recorded operating conditions and taking into account the maintenance records. In the last six years, IES-UPM has offered both indoor and on-site quality control campaigns for more than 60 PV plants, with an accumulated power of more than 300 MW, in close contact with Engineering, Procurement and Construction Contractors and financial entities. This paper presents the lessons learned from such experience.

Keywords: Energy Performance, System Performance, Large Grid-Connected PV Plants, Quality Control, Financing, Bankability.

1 INTRODUCTION

From 2006 large commercial grid-connected PV plants have become an interesting financial product. Nowadays it is still true even without feed-in tariff laws thanks to falling prices of conventional crystalline silicon PV modules. From 2008 to 2014, their prices have decreased nearly sevenfold owing to economies of scale [1]. So, as for any financial product, some tests are appealing for its bankability. In this case, a methodology for yield forecasting and on-site quality control campaigns with the best degree of accuracy are appropriate to make attractive to invest in this kind of energy production systems. From the financial point of view, the key factors are profitability and risk: that is, the annual energy production and the uncertainty that affects it, respectively, as is explained in other publications [2] [3]. The higher the annual energy production and the lower the uncertainty, the more attractive the project.

In conventional PV plants, the improvement of the annual energy is related with the selection of the location (high irradiation) and with the quality of the devices to be installed in the PV plant (modules, inverters, cables, etc.). Besides, in order to reduce the uncertainty of the PV installation forecasting it is important to avoid bad practices that lead to mistakes and failures, and to aim for a predominance of good practices that enable to reduce the maintenance costs [4]. Also, more accurate procedures to perform the yield assessment and the on-site quality control campaigns are essential to reduce uncertainty.

So, the bankability of a conventional PV plant is addressed through the modelling of its energetic yield under a baseline loss scenario followed by and on-site measurement campaign.

2 ENERGY YIELD FORECAST

The energy yield forecast is performed at the beginning of the project and is typically accomplished by means of a simulation exercise. Whichever the software or the model that are used, the simulated PV system yield results from the combination of a hypothetical ideal case with a baseline losses scenario. The latter encompasses all the avoidable energy losses: cables, performance below manufacturer claims, failures, etc. and precisely defines the responsibility of the PV system supplier. The result of this step, in terms of yearly energy production, is based on the cash flow estimations and represents the expectation of the project.

Commercial software for these estimations rely on complex equations that make use of numerous parameters [5] which cannot be easily obtained in the field for large PV plants and which are not adequately supported by PV module manufacturers, because they customarily restrict their guarantee to the power at Standard Test Conditions (STC) of the individual PV modules. In our opinion, increasing the model's complexity also increases the PV module manufacturer's reluctance to provide guarantees of the values on the model parameters.

This is the reason why IES-UPM has developed its own software for energy yield forecast based on the maximum power value and its variation [6]. It only requires data about the characteristic power of the array at STC and also about its thermal and low irradiance behaviour. So, the DC power output of the generator is described by

$$P_{DC} = P^* \frac{G_{ef}}{G^*}[1 + \gamma(T_C - T_C^*)]\left[a + b\frac{G_{ef}}{G^*} + c\,ln\frac{G_{ef}}{G^*}\right]f_{DC}$$

where the symbol * refers to STC, P_{DC} is the DC power output of the PV array, P^* is its nameplate DC power, G_{ef} is the effective global solar irradiance in the plane of the array, G^* is the global solar irradiance at STC (G^* = 1000 W/m^2), T_C is the cell temperature, T_C^* is the cell temperature at STC (T_C^* = 25ºC), γ is the coefficient of power variation due to cell temperature, a, b and c are three parameters related with the variation of module efficiency with solar irradiance and f_{DC} is a coefficient that lumps together all the additional system losses in DC, e.g., technology-related issues, wiring, soiling and shading. It is interesting to note that concerned parameters (P^*, γ, a, b and c) are not only given at the information datasheet, but also considered as a part of the design qualification international norms (a, b and c are obtained from module power corresponding at three irradiance values, which must also be found at datasheets, providing they comply with international standards) [7] [8] [9].

This equation properly defines the performance of a PV array with high accuracy as demonstrated by other authors [10]. Besides, the software includes: the possibility to perform yield assessments from irradiance and temperature input data from a Typical Meteorological Year (TMY) database, a satellite database, or a ground-based meteorological stations or from on-site measurements recorded in PV plants monitoring routines; the simulation for most of the PV tracker routines existing in the current PV market [11] [12]; a model for power converters such as inverters and transformers [13] [14] [15]; and a model to calculate shading losses that improves the previous ones [16].

The AC power at the output of the PV system from this DC power at the inverter entry is

$$P_{AC} = P_{DC}\ \eta_{INV}\ f_{AC}$$

where P_{AC} is the AC power output of the PV array, η_{INV} is the efficiency of the inverter (which can be estimated from several values characteristics of its load curve), and f_{AC} is a coefficient that lumps together all the additional system losses in AC, e.g., technology-related issues and wiring.

Finally, the energy produced during a period of time *T* (a year, for example) is given by:

$$E_{AC} = \int_{t=0}^{t=T} P_{AC}\, dt$$

The accuracy of this initial energy forecast depends on the accuracy of the solar radiation databases selected [3] [17] [18] [19] [20]: the lower the solar resource uncertainty, the lower the energy forecast uncertainty. So, the better option to minimize the uncertainty of solar resource and thereby make the project more attractive would be to possess on-site measurements at the specific location, which are customized for the project's needs (static structures, tracking) [3]. But this requires carrying on previously these specific measurements for at least one year before the start of the project, what is not always possible.

In any case, as this initial energy estimation is directly related to the yearly solar irradiation both figures should be submitted together. That is, the energy production contractual guarantees should include specific clauses for adjusting guaranteed values of energy produced to measured irradiations.

3 RECEPTION TEST CAMPAIGN

The reception test campaign is performed at the beginning of the PV plant operation. It consists of an on-site test whose purpose is to determine the efficiency and the reliability of the main PV plant equipment: PV modules, arrays and inverters.

In fact, the first step in this phase generally is a control of the PV modules at the procurement period. This is typically accomplished by means of indoor testing of a sample of PV modules at a qualified laboratory. These laboratories ensure proper calibration traceability and provide a species of "trustworthiness image" for the whole process of quality assurance. However, there are two noticeable objections that can be made: neither light induced degradation nor irradiance and temperature behaviour are here addressed because prolonged Sun exposure is needed.

So, an additional on-site test is needed later: an on-field testing performed during a short period of time just after the PV plant begins to operate, once the modules have been exposed outdoor and have been injecting energy into the grid for several weeks.

Typically, the acceptance criteria is established on the basis of a Performance Ratio (*PR*) value. So, a PV plant will be accepted if

$$PR = \frac{E_{AC,REAL}}{P^*_{NOM}\ \frac{\int_{t=0}^{t=T} G_{ef}\, dt}{G^*}} \geq PR_{GUARANTEED}$$

where $PR_{GUARANTEED}$ is specified at the contract (its value is typically around 80%), $E_{AC,REAL}$ is the real AC energy injected into the grid during the test period *T* (it can be obtained from the energy meters as the difference between the reading at the end of the test and its initial value) and P^*_{NOM} is the contractual nominal power of the PV array/plant under study. So, *PR* can be directly calculated without any kind of modelling because it only requires integrate the G_{ef} records. A key inconvenient of this approach is that the *PR* value is time and site dependent: it depends on the operation temperature which, in turns, depends on the climatic conditions and, therefore, on the site and on the time of the year. So, the mere *PR* is generally not adequate for sub-year periods (days, weeks, months).

As an example, Fig. 1 shows the weekly *PR* variation (squares) measured at a PV plant during one year. The figure shows values larger than 1 because the real peak power of modules is slightly larger than the nominal value and because winter is typically very sunny but very cold in the location of this PV plant. The key point here is to observe that *PR* varies up to ±10% along the year and even up ±5% along the same month.

If time-dependent unavoidable energy losses are removed from the performance ratio we obtain what can be called "performance ratio at STC"

$$PR_{STC} = \frac{PR}{\prod_u (1 - \Delta E_u)}$$

where ΔE_u are the energy losses and "*u*" extends to unavoidable phenomena such as thermal losses (due to $T_C \neq T_C^*$) and variation of module efficiency with irradiance. So, the PR_{STC} calculation requires records of G_{ef} but also records of T_C and modelling. For the measurements of G_{ef} and T_C we recommend to use reference PV modules of the same technology than the modules of the PV array, previously stabilized and calibrated in a recognized laboratory. This ensures that both PV array modules and reference modules will have similar spectral, angular and thermal responses and a similar degree of soiling, thus minimizing the uncertainty of the measurements of these parameters [21] [22] [23]

[24] [25].

As can be seen in Fig. 1, PR_{STC} (triangles) is significantly more constant than *PR* (in the graph there are only two anomalous values, which are probably related with bad weather or with problems at the temperature measurements). In our opinion, the advantages derived from the use of PR_{STC} is large enough to pay the price of, first, recording operation temperature and, second, modelling just based on PV manufacturer datasheet information.

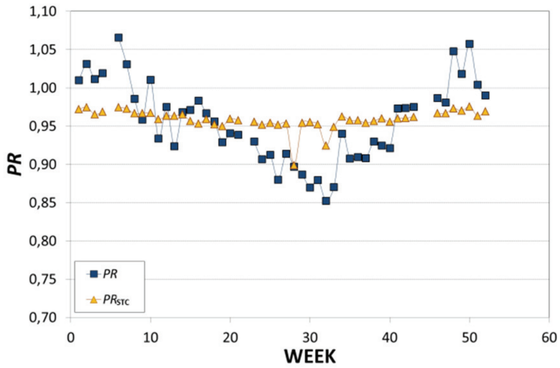

Figure 1: Weekly variation of *PR* and PR_{STC} measured at a PV plant during one year.

Another drawback of testing just the *PR* value (even the PR_{STC} value) is that the real behaviour of the PV plant is not addressed (that is, the real power of the PV arrays, the real efficiency of the inverter, the inverter saturation, the behaviour under shading, etc.). Typical commissioning testing only check if the PV plant's energy yield is over the guaranteed values, but we think that it is very useful to assess the performance of not only the PV plant, but also its main devices: PV arrays and inverters.

Therefore, a better and more accurate option for the characterization of the global behaviour of the PV plant is to compare the real energy production during the test period (one or a few weeks) with the energy output calculated from the corresponding recorded operating conditions (G_{ef} and T_C) and to adopt the same baseline losses scenario defined at the energy yield forecast phase: thermal losses, variation of module efficiency with irradiance, shading, DC cable losses, inverter efficiency, inverter saturation, AC cable losses, etc.. The characterization of PV arrays and inverters can be done with an accurate wattmeter by measuring and recording simultaneously, with a sampling time equal to or lower than 5 minutes, G_{ef} and T_C, from the reference modules, and P_{DC} and P_{AC}, from the inverter entry and output [26] [27].

The AC power records allow characterizing the AC power response, as shows Fig. 2. In the graph are plotted the experimental AC power values ($P_{\mathrm{AC,EXP}}$) versus the simulated ones obtained from the measurements of G_{ef} and T_C and applying the previous equations ($P_{\mathrm{AC,SIM}}$). So, not only normal operation (linear dotted behaviour) but also anomalous situations such as shading over sensors or over PV array modules due to clouds, strings switched off, inverter saturation, inverter stops, etc. can be very properly analyzed with this test.

The DC power records allow characterizing the real peak power of the PV array with high accuracy, as shows Fig. 3. First, the DC records related to anomalous situations and to low irradiances should be removed previously. This issue has been already reported in other works [25] [26].

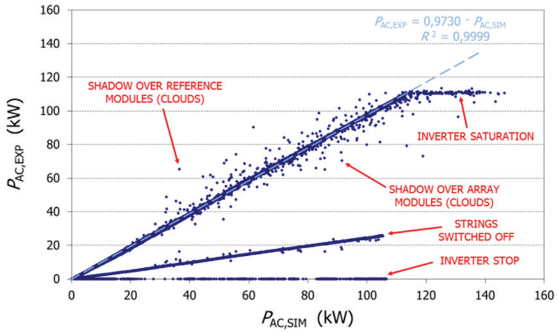

Figure 2: AC power response of a 110 kW nominal power PV array measured on-site with a wattmeter. The normal operation is represented by the linear dotted behaviour. The other anomalous situations can be perceived in the graph: shadow over sensors or over PV array modules due to clouds, strings switched off, inverter saturation and inverter stop.

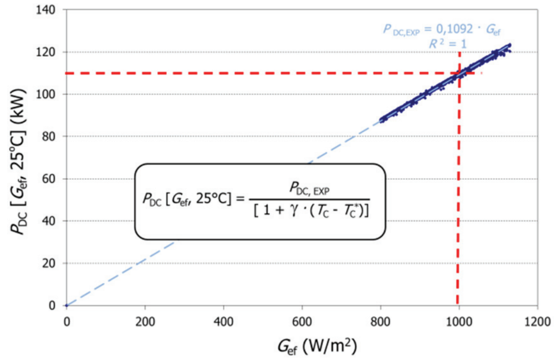

Figure 3: DC power corrected at 25ºC of a 110 kW nominal power PV array measured on-site with a wattmeter. The DC power records related to anomalous situations and to low irradiances should be previously removed to obtain the DC peak power value at STC (the value indicated by the red dotted lines in the "y" axis).

This peak power characterization can also be done by means of I-V tracers. Nevertheless, due to the module temperature, the dispersion uncertainty of a single measurement (a single I-V curve provides a single value of maximum power) tends to be large. It should be commented that we have built our own equipment [28] that is now able to measure currents above 1000A. In fact, we have measured the I-V curve of an 800 kW PV array (Fig. 4). This is, as far as we know, the largest PV array ever tested with this kind of devices all around the world [29].

Finally, the simultaneous AC and DC power measurements also allow characterizing the inverter efficiency. Fig. 5 shows an example of the efficiency curve of a 100kW inverter. A detailed study of the characterization and simulation of inverters has been reported in other works [14].

It is important to notice that all these additional tests allow characterizing the real losses scenario of the PV installation during the reception test campaign.

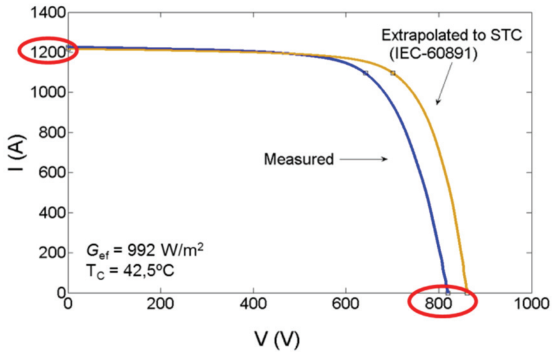

Figure 4: I-V curve of an 800 kW nominal power PV array measured on-site with the capacitive load implemented by IES-UPM.

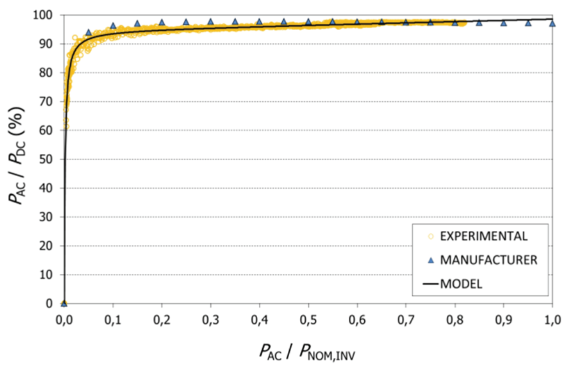

Figure 5: Efficiency of a 525kW inverter: as reported by manufacturer (triangles), on-site measurements (circles), and modelling from measurements (solid line).

Additionally to the one-week *PR* test, PV generators are generally inspected by means of infrared cameras that allow detecting possible hot-spots. The major hindrance related to these procedures is that there is currently a lack of widely accepted criteria to deal with hot-spots anomalies. A relevant example is the text of the IEC concerning commissioning test [30] and a draft of a new IEC relating to hot-spots [31]: they describe the hot-spot phenomena and how to capture, process and analyze the infrared images, but that description is not useful to solve a conflict between PV plant vendors and buyers concerning hot-spots. Not surprisingly, these conflicts relating to hot-spots are a frequent reason for consultancy at our institution.

So, after some experiments performed in real PV plants affected by hot spots [32] [33] [34], we propose an acceptance/rejection criteria [35]:

- PV modules with hot-spots larger than 20ºC should be rejected because their lifetime will be probably shorter.
- PV modules with hot-spots lower than 20ºC but larger than 10ºC are tested. Those of them that exceed the allowable peak power losses fixed at standard warranties (measured as a decrease in the operating voltage in relation to a non-defective module of the same string) should be rejected).
- PV modules with hot-spots lower than 10ºC are accepted, except in the case that one or more by-pass diodes are defectives.

4 PERFORMANCE ANALYSIS OF THE FIRST YEARS

Finally, the performance analysis is carried out at the end of the first or second year of operation and, again, it consists of comparing the real energy production with the one calculated from the recorded operating conditions and taking into account the maintenance records, as well as the corresponding visual and thermal revision of the PV array. As the considered time is large enough to be representative of routine operation, not only the technical quality of the PV plant equipment but also the quality of the operation and maintenance procedures is addressed at this step. Difficulties here derive from possible technical PV failures and inconsistencies on the recorded operating condition data and on the maintenance log books.

Table I shows the yearly energy production at 12 different commercial Spanish PV plants that had been previously analyzed in the reception test campaign. The first column shows the nominal power of the PV plant; the second column shows the real yearly yield, obtained from the energy meter readings; the third column shows the modeled yearly yield taking into account the records of G_{ef} and T_C from the reference modules, the maintenance log book and the real losses scenario obtained during the reception test campaign; and the fourth column shows the difference between the real and the modeled yearly yield. As can be seen, the result conveys good accuracy. So, it is a good argument in favor of measuring the operating condition data with reference PV modules similar to those installed in the PV plants and to model considering just the maximum power point and its variation.

Table I: Real and modeled Yearly Yield (YY) at 12 different commercial Spanish PV plants.

Nominal power (MW)	Real YY (kWh/kW)	Modeled YY (kWh/kW)	Error (%)
2	2038	2067	1.4
2.16	2056	2095	1.9
2.95	2050	2096	2.2
2	2194	2163	-1.4
1.5	2074	2032	-2.1
1.4	1561	1597	2.3
2.03	2142	2140	-0.1
11.2	2016	2038	1.1
2.1	2204	2198	-0.3
1.9	2320	2279	-1.8
9.7	2108	2111	0.1
25.3	1594	1616	1.4

5 SUMMARY

This paper has presented the lessons learned by IES-UPM during the last six years relating the yield assessment and on-site quality control campaigns for more than 60 PV plants (more than 300 MW). Some particularly relevant aspects of our method are:

- Energy modeling solely based on the only guaranteed specifications from the PV module manufacturer: maximum power point and its variation.
- Measurement of both in-plane irradiance and module temperature by means of dedicated PV

reference modules, in order to minimize uncertainty.

- Acceptance criteria based on the performance ratio corrected to STC, PR_{STC}, to overcome the time inconstancy of the simple *PR*.
- In-field measurements of AC power response, DC peak power at STC and inverter efficiency curves up to 1 MW to characterize the behaviour of the individual PV plant devices.
- A proposal of a criteria to deal with hot-spots in modules, based on temperature increments and on voltage losses.

5 ACKNOWLEDGMENTS

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BANKABLE PROCEDURES FOR THE TECHNICAL QUALITY ASSURANCE OF LARGE SCALE PV PLANTS

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PV CROPS

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1. INTRODUCTION

- Strict technical quality assurance procedures are essential for large PV plant bankability:
  - Energy yield forecast; reception test campaign; performance analysis of the first years of operation.
- The higher the annual energy production and the lower the uncertainty, the more attractive the project.

2. ENERGY YIELD FORECAST

- IES-UPM procedure: simulation exercise of a hypothetical ideal case with **a baseline losses scenario** and with **a model based on parameters guaranteed by the manufacturers** and **on operating conditions**.

Effective irradiance on array plane — **Cell temperature** — **Other DC losses: wiring, soiling, shading…** — **Inverter power efficiency** — **Other AC losses: wiring, technology issues…**

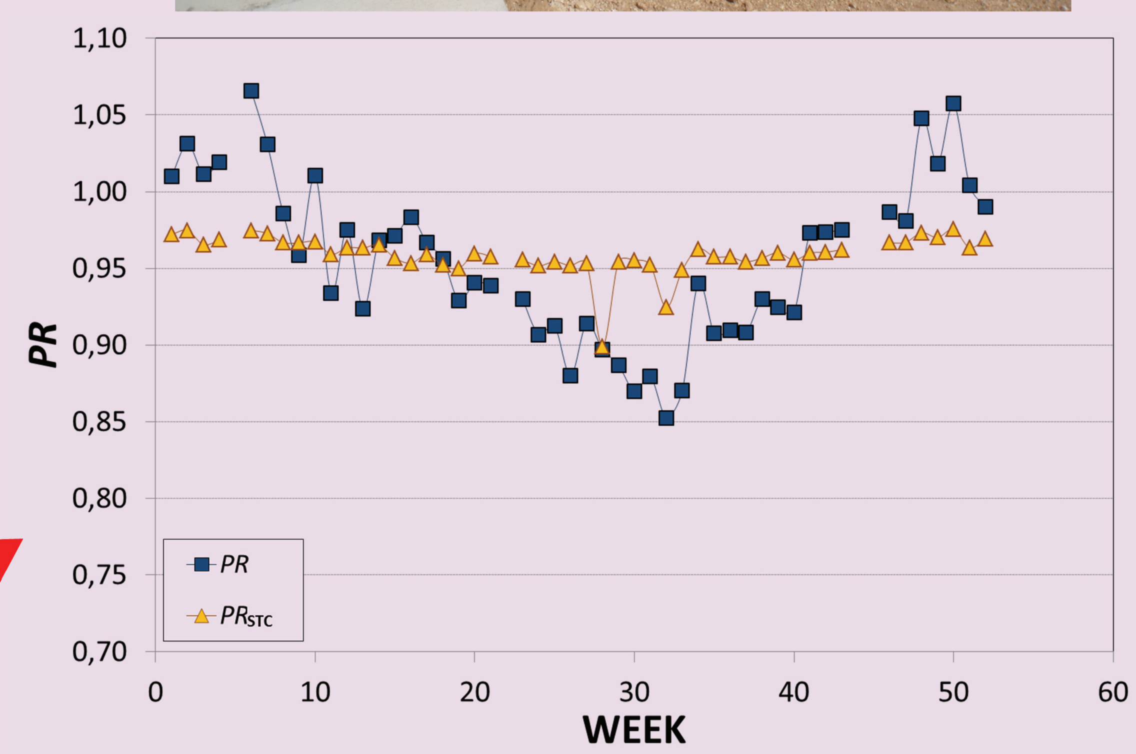
$$P_{DC} = P^{*}\frac{G_{ef}}{G^{*}}\left[1+\gamma\left(T_C - T_C^{*}\right)\right]\left[a + b\frac{G_{ef}}{G^{*}} + c\,ln\frac{G_{ef}}{G^{*}}\right]f_{DC} \qquad P_{AC} = P_{DC}\,\eta_{INV}\,f_{AC} \qquad E_{AC} = \int_{t=0}^{t=T} P_{AC}\,dt$$

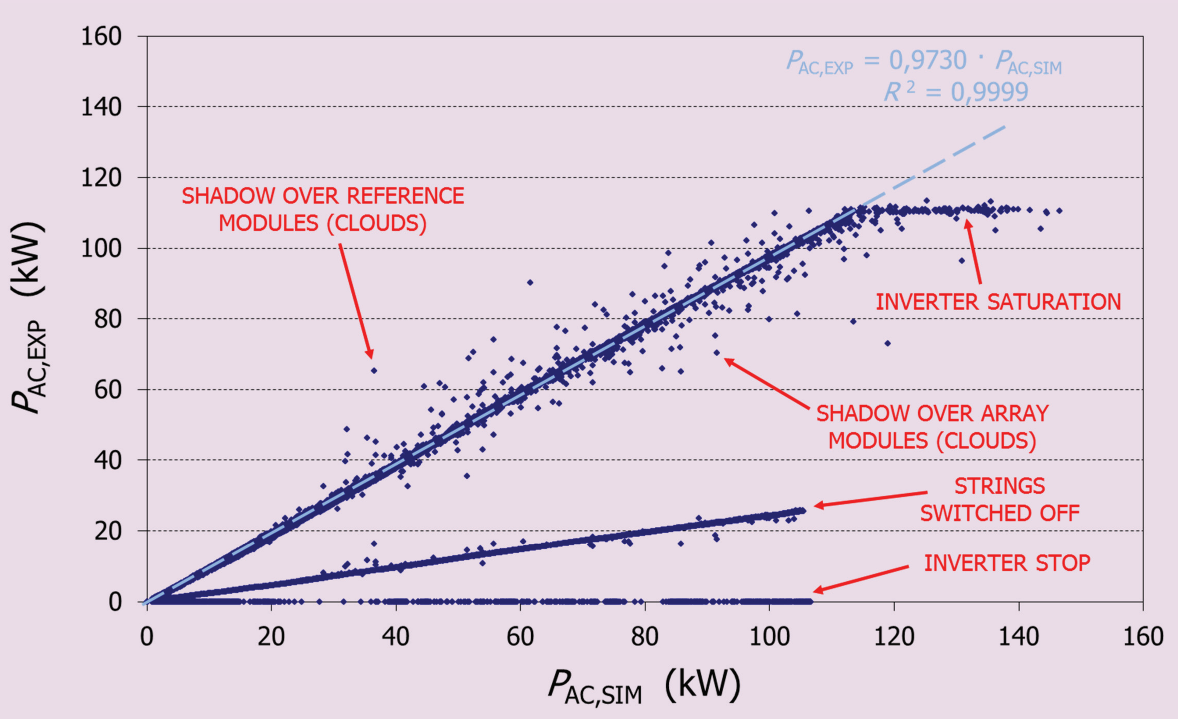
Module nameplate DC power — **Coefficient of module power variation due to T_C** — **Parameters related with the variation of module efficiency with G_{ef}**

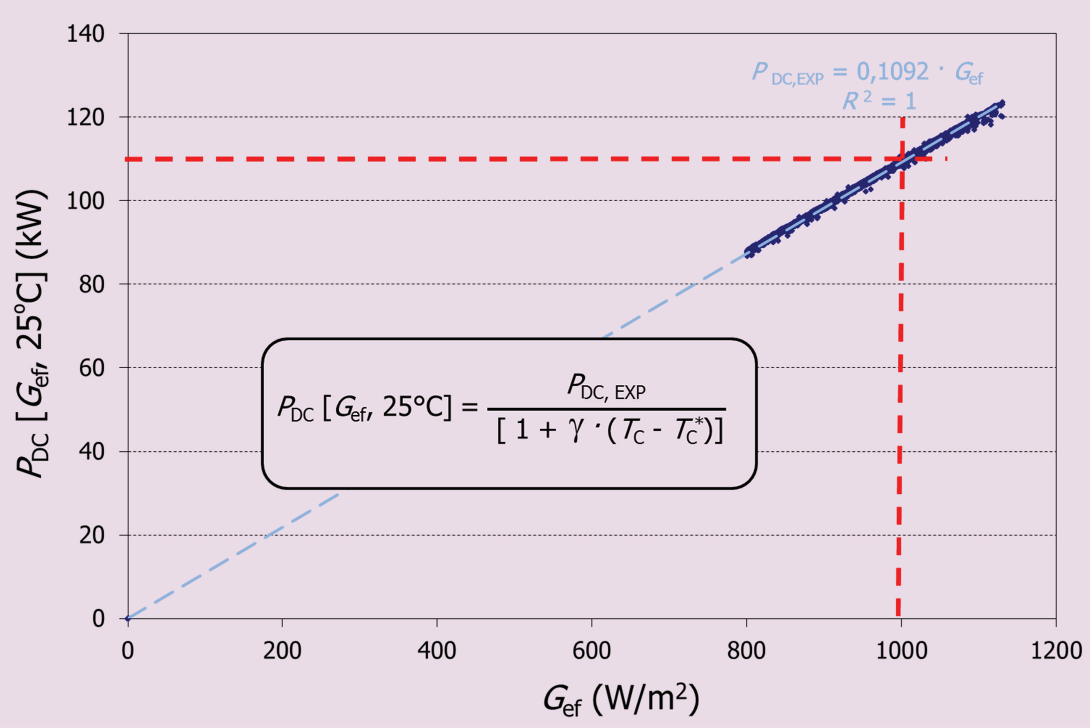
- Uncertainty is reduced if there are previous on-site measurements of G_{ef} and T_C from reference PV modules of the same technology.

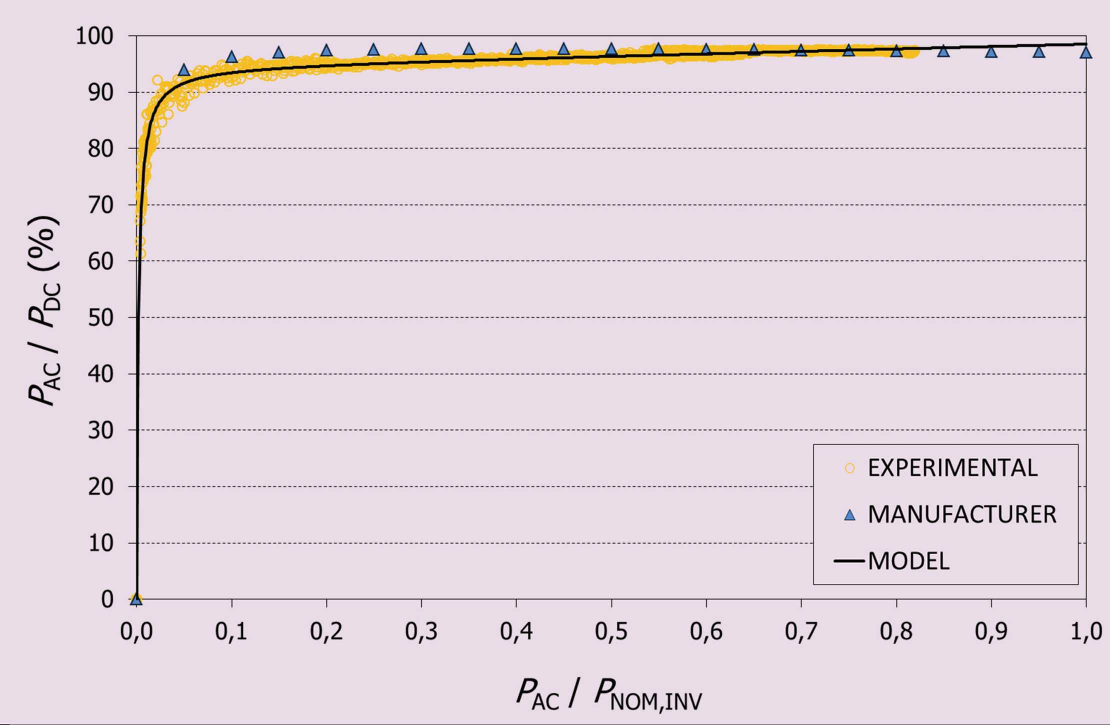
3. RECEPTION TEST CAMPAIGN

- Short duration tests (one – two weeks) at the end of commissioning.
- Usually based on a control of PV modules at the procurement period and an analysis of performance ratio (*PR*) during one-two weeks.
- IES-UPM procedure:
  - G_{ef} and T_C measured from reference PV modules (uncertainty is reduced).
  - Analysis of *PR* at Standard Test Conditions (PR_{STC}, less time-dependent).
  - Real behaviour of PV plant (actual losses scenario): AC power response, DC power characterization, inverter efficiency.









4. PERFORMANCE ANALYSIS OF THE FIRST YEARS

- Comparison between actual yearly yield (YY) and modeled yearly yield (calculated with the actual losses scenario and the recorded G_{ef} and T_C).

  The result conveys good accuracy.

Nominal power (MW)	Real YY (kWh/kW)	Modeled YY (kWh/kW)	Error (%)
2	2038	2067	1.4
2.16	2056	2095	1.9
2.95	2050	2096	2.2
2	2194	2163	-1.4
1.5	2074	2032	-2.1
1.4	1561	1597	2.3
2.03	2142	2140	-0.1
11.2	2016	2038	1.1
2.1	2204	2198	-0.3
1.9	2320	2279	-1.8
9.7	2108	2111	0.1
25.3	1594	1616	1.4

We are looking you forward in the parallel event (Wednesday 24th Sept 9–12 am): "Grid-connected PV systems: Field testing, performance monitoring, and energy storage"