

# CPV SYSTEMS RATING, RESULTS AND LESSONS LEARNED AT ISFOC

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## ABSTRACT

ISFOC has finalized the installation of the 1<sup>st</sup> phase demonstration plants and the acceptance procedure is in progress. To determinate the Nominal power, it has been necessary to develop a Power Rating Procedure which is being validated with the acceptance works. The Power of each Concentrator is measured in operating conditions and translated to Nominal Conditions (850W/m<sup>2</sup> DNI and 60°C cell temperatures) to finally achieve the Nominal Power in direct current of the entire plant. For the Nominal Power in alternating current a control of the Energy Production of the plant is made during seven days. So Far, 300kW have been rated with excellent results, as the DC Nominal Power is reaching the expected value. Also, these acceptance tasks are highlighting some important issues for future R&D lines, like the wind influence in the electrical performance of a CPV and the necessary relation between operating cell temperature and ambient conditions in order to achieve precise Energy prediction models.

## INTRODUCTION

ISFOC has already finished the construction and installation of 800kW CPV plants at the site Puertollano I (see Fig.1) of the 1<sup>st</sup> phase of the ISFOC project.

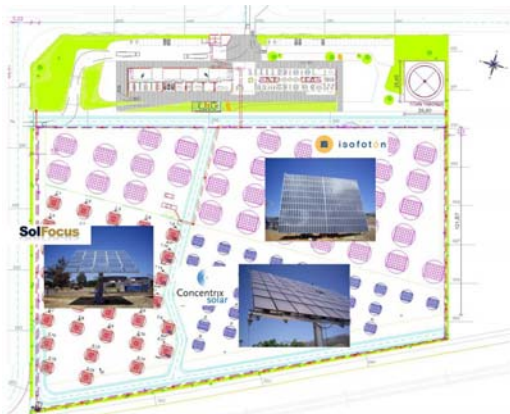


Fig. 1 ISFOC installations at Puertollano I

The installation consists of 8 CPV plants of 100kW each, totally independent and connected to a common transformer substation for the evacuation of the energy to

the grid. Our partners in these installations are Concentrix Solar (200kW) from Germany, SolFocus (200kW) from USA and Isofoton (400kW) from Spain.

These installations are currently operational connected to the grid and ISFOC is working in the acceptance of the plants [1]. In these paper only the Power Rating procedure at ISFOC for a CPV plant is described, together with the available results and the analysis made to the data.

## CPV SYSTEMS POWER RATING PROCEDURE AT ISFOC

Nowadays there is no official procedure for rating the electrical performance of a CPV system. In fact, the IEC TC82 WG7 is now working in this task and ISFOC, together with the IES-UPM; is one of the institutions in charge of developing the CPV rating standards. ISFOC is providing instrumental information into this working group, as our experience in the study of various technologies deployed at large scale is unique.

ISFOC has already defined a draft procedure for CPV Power Rating (in direct current and alternating current). This procedure is being validated through the acceptance of these first demonstration plants, concluding with the validation of the method including the experience obtained in the field and subsequent analysis of the data.

For the determination of the Nominal Power of a CPV plant in Standard Test Conditions (STC), first the Nominal Power in direct current (DC) has to be obtained and this data is going to be used for the final determination of the Nominal Power in alternating current (AC).

## Standard Test Conditions at ISFOC

In order to compare different CPV technologies it is necessary to define which are going to be the Standard Test Conditions (STC) in which the Nominal Power of the CPV system it is going to be expressed.

The Standard Test Conditions used by ISFOC are:

- DNI=850W/m<sup>2</sup>
- Operating cell temperature=60°C

ISFOC uses the operating cell temperature instead of ambient conditions (ambient temperature and wind, speed and direction) because, at the moment, it is very difficult to determine the influence of those variables in the electrical performance of a CPV system.

### DC Power Rating Procedure

The purpose of the DC Power Rating is to obtain the DC Nominal Power in STC of the 100kW plants installed.

As ISFOC plants are demonstration plants and there is no official procedure, we have decided to characterize all the concentrators of the plant to determine the DC Nominal Power of the entire plant. So, we are measuring the maximum power of each one of the concentrators in the operation conditions and this value is translated to the STC in order to obtain the Nominal Power of the concentrator. Therefore, the sum of the Nominal Power of all the concentrators in the plant is going to be the value for the DC Nominal Power of the complete plant in STC.

For measuring the maximum power of a concentrator and the operation conditions the following variables are registered using the equipment specified (see Fig.2 and Fig.3):

- For obtaining the maximum power we register the I-V Curves of the concentrator with an automatic I-V Curve Tracer [2].
- The Direct Beam Irradiance (*DNI*) is registered with two pyrheliometers installed in two independent trackers to assure a good value for this variable which it is the energy input for a concentrator.
- For calculating the operating cell temperature we register the heat-sink temperature, with several thermal sensors installed at the back plate of the module behind the cells.
- Other ambient conditions are monitored using the meteorological station in order to complete the measurements with the ambient conditions (temperature and wind in direction and speed) that are surrounding the characterization works.
- Finally, the DNI spectrum is measured with a spectroradiometer in order to compare the real spectrum with the standard.

In order to obtain a reliable value for the measured power it is necessary to establish some limitations to the ambient conditions that are surrounding the measuring works: The DNI has to be higher than 700W/m<sup>2</sup>, assuring that the sky is clear and with no clouds around the sun and the wind speed has to be lower than 3.3 m/s. This last limitation is due to the thermal stabilization of the concentrator, as wind speed is a factor which influences the heat dissipation of the system [3].

All of these variables are registered during a selected period of time in order to achieve a precise value for the power. For this purpose it is necessary to have a

period of time where the measurements are made with DNI stable and with the concentrator thermally stabilized.

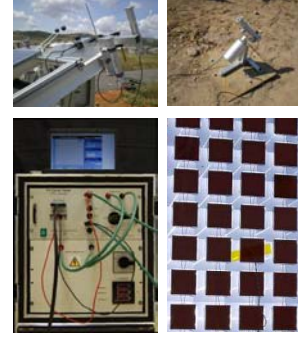


Fig. 2 ISFOC equipment for registering the power and the operations conditions



Fig. 3 ISFOC meteorological station

For the translation of the measured power to the Nominal Power in STC, the equations presented in our call for tenders [4] are used. These equations are defined for multi-junction cells, being J the number of junctions of the cell. The necessary parameters for the calculation are defined in Table 1.

Table 1: CPV Characteristic Parameters

$N$	Number cells connected in series
$I_{Lj}$	Short-Circuit current for each junction
$R_s$	System series resistance (cells and wires)
$E_{gj}$	Band gap for each junction
$V_{OC}$	System Open-Circuit voltage
$R_{th,sys}$	Thermal resistance system

$$I^2 = I^1 \cdot \frac{B^*}{B^1} \quad (1)$$

$$V^2 = V^1 + N \cdot \frac{0.0257 \cdot (T_{cell}^* - T_{cell}^1)}{297} \cdot \ln \left( \frac{\prod_j (I_{Lj} - I^1)}{\prod_j I_{Lj}} \right) - I^1 \cdot \left( \frac{B^* - B^1}{B^1} \right) \cdot R_s + 3 \cdot N \cdot \frac{0.0257 \cdot T_{cell}^*}{297} \cdot \left( \frac{B^*}{B^1} \right) + \left( N \cdot \left( \sum_j E_{gj} \right) - V_{OC} \right) \cdot \left( 1 - \frac{T_{cell}^*}{T_{cell}^1} \right) \quad (2)$$

$$T_{cell} = T_{h-s} + B \cdot R_{th,sys} \quad (3)$$

With eq(1) and eq(2) The current ( $I$ ) and voltage ( $V$ ) measured are translated from the operation conditions ( $B^1$ ,

$T_{cell}^1$ ) to the STC ( $B^*$ ,  $T_{cell}^*$ ). Eq(3) is used to obtain the operating cell temperature ( $T_{cell}$ ) from the measured temperature at the heat-sink ( $T_{h-s}$ ). It is necessary to have the system thermally characterized with the thermal resistance; this parameter is defined like the heat dissipation between the cell and the back plate of the module.

This method is repeated for all the concentrators installed in the plant, obtaining then the characterization of the whole plant. As it has been said before, the DC Nominal Power of the plant is the sum of all the Nominal Power values for all the concentrators of the plant.

### AC Power Rating Procedure

Once we have obtained the DC Nominal Power of the plant, the AC Nominal Power has to be determined. This AC rating procedure consists of a control of the Energy produced during a period of time.

We use the DC Nominal Power of the plant for the calculations to obtain the theoretical Energy produced by the plant. For this purpose the DNI data and the heat-sink temperature from several modules from different concentrators in the plant (selected in a random way) are stored.

The DC Nominal Power obtained is translated into its value at each one of the measured operation conditions using eq(1), eq(2) and eq(3). With these values for the theoretical DC Power and the inverter efficiency the theoretical AC Power is calculated. If these values are numeric integrated during all the AC rating period the theoretical Energy production is delivered.

Comparing this theoretical Energy production with the real data of the energy meter of the plant, a factor ( $F$ ) is defined which represents the real performance of the plant due to errors in the tracking function along the complete days, the modules performance in different conditions (spectrum, temperature, low DNI, shadowing...).

Finally the AC Nominal Power ( $P_{AC}$ ) of the plant is calculated with eq(4) using the inverter efficiency ( $\eta_{inv}$ ) and the factor  $F$  with the DC Nominal Power ( $P_{DC}$ ).

$$P_{AC} = P_{DC} \cdot \eta_{inv} \cdot F \quad (4)$$

When the connection to the grid is unavailable, the AC Nominal Power is calculated using only the efficiency of the inverter in eq(4) to correct the value of the DC Nominal Power.

This procedure has also some limitations. The period for the rating has to assure medium sunny days and if the plant goes to safety position due to high speed wind the theoretical energy generated during this situation should not be considered for calculations.

## DC POWER RATING, DATA ANALYSIS

As an example of the data analysis performed, the results of the DC power rating of a plant are presented in normalized values.

For the determination of the Nominal Power of a concentrator, first we study the ambient conditions to check if they fulfill the requirements (see Fig.4).

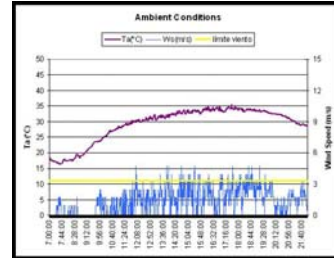


Fig. 4 Ambient conditions measurements

If the measurements are represented graphically, we are able to select a period of time where the measurements are suitable for the calculations of the Nominal Power; the system has to be thermally stabilized (see Fig. 5) and DNI stable (see Fig. 6).

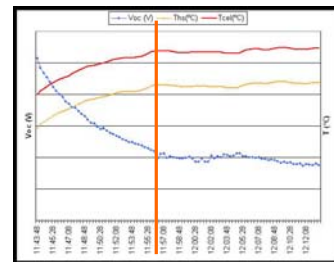


Fig. 5 Thermal behavior of a CPV

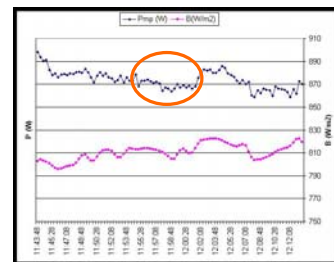


Fig. 6 DC Power generated vs. DNI

Fig. 5 represents the temperature evolution (heat-sink measured and cell calculated) versus the open circuit voltage. This graph represents, in a very good way, the thermal behavior of the system and it is used to reject measurements where the system is not thermally stabilized.

Fig. 6 represents the evolution of the maximum power generated versus the DNI. In this graph we can observe how the performance of the system depends directly of the DNI. And through this graph we select a period where the DNI is most stable so that a final average value of the power with less dispersion can be obtained.

For each one of the measurements selected we translate the I-V curve measured to the STC (see Fig. 7) using eq(1), eq(2) and eq (3).

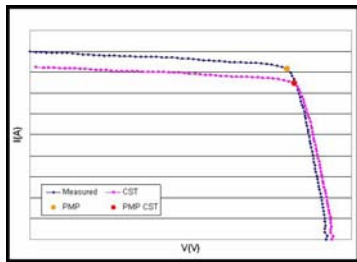


Fig. 7 I-V Curve measured and translated to STC

Repeating these calculations to all the measurements selected we achieve an average value for the Nominal Power of the concentrator. The dispersion in the calculations is also obtained.

Applying this procedure to all the concentrators of the plant we can determine the Nominal DC Power of the whole plant, but the analysis made to each concentrator has to be checked.

Fig. 8 is a box-plot representation of the Nominal Power calculations for all the concentrators (a normalized value with the theoretical value) of one plant. This graph shows the value for the Nominal Power of each concentrator as well as the dispersion from the calculations. A maximum deviation allowed of  $\pm 10\%$  for the Nominal Power is referenced in the graph.

This graph is a very useful representation in order to analyze if the rating process of the plant has been done in an adequate way.

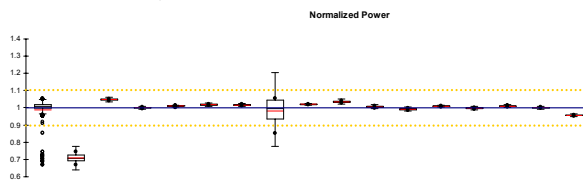


Fig. 8 Rating results for a whole plant

In this particular case we can see two anomalous points.

- The first point corresponds to a concentrator which its Nominal Power calculated is only about the 70% of the expected value. Checking again the measurements and calculations we

find out that the problem was related to the tracking of the systems, which was not well aimed to the sun during the measurements.

- The second point is one where the dispersion obtained from the calculations is about the 20%. Again, checking the data we find out that the measurements were made a day where the ambient conditions were out of the requirements; the DNI was not stable, decreasing from  $900\text{W/m}^2$  to  $600\text{W/m}^2$  during the measuring period.

Once the problems are solved we can say that the acceptance of a plant has been done in an adequate way when the Nominal Power of all the concentrators is between the  $\pm 10\%$  of the expected value and with low dispersion.

## RESULTS, CONCLUSIONS AND FUTURE R&D LINES

ISFOC has already completed the installation of the first 800kW at Puertollano I and we are working now in the acceptance of this 8 CPV plants. Up to now 300kW have been already measured and analyzed, in that way the DC Nominal Power of 3 of the CPV plants have been calculated. The works for measuring another CPV plant is now in progress, at the same time we are repeating the measurements of the uncertain results, to assure the expected values for all the concentrators rated.

Fig. 9 represents the DC Nominal Power calculated for all the concentrators rated. From the results represented in the graph we can extract some conclusions. The Nominal Power of all the concentrators rated is between the  $\pm 10\%$  of the expected Nominal Power, more in detail we can see that the Nominal Power of about the 50% of the concentrators rated is higher than the expected value, which it is a very good value for the first CPV demonstration plants installed, this means that the CPV systems actual performance is reaching the expected values.

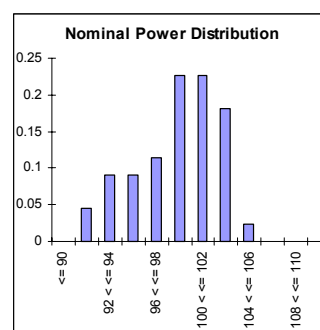


Fig. 9 Nominal Power distribution of all the concentrators

At the moment of this conference ISFOC has not begun with the AC rating as sunny periods of time are needed, therefore rating will start when good operation conditions are present. The AC Power Rating procedure is

ready and waiting to be tested and finally validated with the acceptance of the plants.

As the connection to the grid is available, we have started with some preliminary analysis of the Energy production data (see Fig.10), which it is very useful for the AC Power Rating, showing how the actual performance of each concentrator is during a full day of operation.

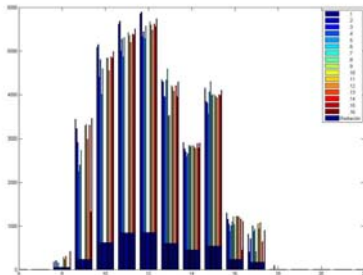


Fig. 20 Daily Energy Production of a plant with the contribution of each concentrator

The works for the acceptance of the plants (measuring works and data analysis) are pointing out some important issues that should be studied more in detail, opening in this way future R&D lines to study:

- At our installations at Puertollano I we have found out that wind speed is often higher than the limit value (3.3m/s) established for the thermal stabilization of the system. In that way we have been forced to characterize some concentrators with higher wind speed values. These measurements were studied more in detail and some of them were rejected. Therefore it is a important and urgent future work to establish a real limit to the wind speed and also including the wind direction in this study because only the wind that affects to the thermal behaviour should be rejected.
- The value of DNI for STC is going to be tested as we can study with actual data the average values for the DNI in locations where the CPV is feasible.
- The independent tracker used to measure the DNI allows us to study also how the tracking performance is and how it evolves in time.
- ISFOC is now beginning to test different methods to obtain the nominal power for a CPV as there are many different CPV technologies in different ambient conditions. At the same time the IEC TC82 WG7 has now proposed different methodologies to obtain the Nominal Power and Energy Production of a CPV system or plant, so ISFOC is going to try all the methods to find out which one of them is the most accurate.
- Finally, to obtain good models to predict the CPV energy production it is necessary to study the correlation between the operating cell temperature and the ambient conditions. Because ISFOC is going to have all these data

registered, we are initiating the works related with this task.

## ACKNOWLEDGEMENTS

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