Demonstrating CPV performance using power rating

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This paper first appeared in the fifth print edition of *Photovoltaics International* journal.

ABSTRACT

Armed with the aim of generating a knowledge base on CPV technology, ISFOC has installed 1.4MW of CPV and is executing up to a total of 3MW of power plants incorporating seven different technologies, all scheduled for completion in 2009. These pilot plants are being established to assist the industry in the setting up of pilot production lines and to obtain very valuable information such as reliability, suitability and production [1]. Rating measurement approaches have been proposed by ISFOC, but there remains a need for an international standard that is accepted by the CPV community. This paper presents ISFOC's proposed standards set and outlines the methodology adopted by the company in this respect.

Introduction

In order to generate key knowledge on CPV technology, ISFOC set out to establish a rating measurement for power plant acceptance, following its own methodology. Based on the equations of the Shockley model, only one measurement is needed to establish the nominal power of the CPV system. This procedure measures heat-sink temperature to calculate the cell temperature through the thermal resistance, as well as direct normal irradiation (DNI) using a pyrheliometer and the I-V curve [2]. ISFOC has proposed this approach to demonstrate the performance of CPV modules and plants, and with its experience in the sector, ISFOC is in the privileged position of contributing to the definition of new standards for the power and energy rating for CPV systems

Power rating: IEC Committee

The Working Group 7 of the IEC TC82 Committee is working actively to develop the new standards needed for the improvement of the CPV technology and market.

A standard that is sorely needed is that of power rating, as it is the only way of comparing the performance of modules from different manufacturers. This subgroup of Group 7 of the TC82 of the IEC is headed by Sarah Kurtz (NREL), who has presented to the IEC Committee a 'New Work Item proposal' with the title "Concentrator Photovoltaic (CPV) Module and Assembly Performance Testing and Energy Rating: Part 1: Performance Measurements and Power Rating - Irradiance and Temperature".

The purpose of this test standard is to define a testing and rating procedure, which provides the CPV module power (watts) for a set of defined conditions. Secondly, the standard would provide a method of determining a set of characterization parameter values for the module.

This standard is based on the IEC 61853-1 (power rating methodology for flat-plate PV modules) [3], which provides the PV module power (watts) at maximum power operation for a set of defined conditions. In the case of CPV modules, the set of conditions is varied.

As the power depends of the radiation and temperature level, Table 1 shows the layout for logging power measurements at different levels of radiation and temperature. Of course, this set of parameters and the procedures to carry out the measurements need to be adapted to the CPV conditions in question.

"The challenges faced by these new solar simulators will be temperature and radiation level control, as well as the spectrum to test the CPV modules at different conditions."

The IEC 61853-1 standard outlines two possible procedures for carrying out this test: using a solar simulator for the indoor measurements or using natural sunlight.

Indoor measurement challenges

One of the best ways of carrying out the measurements under the set of conditions described in Table 1 is by performing these measurements indoor under controlled conditions. As CPV requires collimated light, these measurements must be taken with a solar simulator. Some solar simulators under development have demonstrated very good results [4] and it is hoped that they will be used to characterize CPV modules under the conditions of this new standard.

The challenges faced by these new solar simulators will be temperature and radiation level control, as well as the spectrum to test the CPV modules at different conditions.

As ISFOC does not yet have a solar simulator, this procedure has to date been checked in outdoor conditions.

Outdoor measurements

In the case of natural sunlight, the PV standard describes a procedure of shading the modules for changing temperature conditions or the filtering of radiation to modify its value. However, this methodology needs developed very concisely and carefully, given the difficulty of performing the procedure due to the size of some CPV modules. It is also a concern that the filter of radiation could have spectrum variations, a concern that could be more important in this type of module than for flat PV.

In checking the standard, ISFOC used this method in a whole concentrator system where it is impossible to use shades or filter to change the conditions.

Irrad.	Air Mass	Module temperature			
		15°C	25°C	50°C	75°C
1100	AM1.5				
1000	AM1.5				
800	AM1.5				
600	AM1.5				
400	AM1.5				
200	AM1.5				

Table 1. Set of parameters for IEC 61853-1.

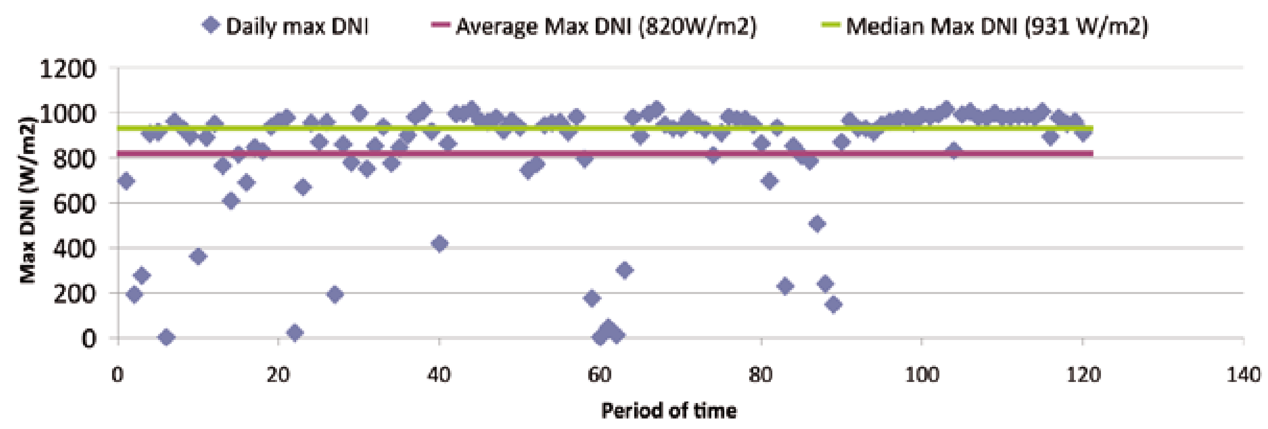

Figure 1. Daily values of max DNI showing average and median line in Puertollano between the months of January and April 2009.

To remedy this, measurements were taken on different days and at different ambient temperatures and radiation levels in an attempt to satisfy the conditions requirements.

Measurement methodology

All measurements taken for this paper were carried out at ISFOC facilities in Puertollano (Spain) using two concentrators: A and B. These HCPV systems feature concentrator modules on a two-axis tracker. Both concentrators have a nominal power of 6100W at 850W/m^2 and 60°C of equivalent operating cell temperature.

The standard ISFOC measurement equipment [5] was used in this procedure.

The I-V curve of the system is measured with a capacitive charge using multirange I/V tracing equipment developed by the Institute of Solar Energy from the Universidad Politécnica de Madrid. This equipment incorporates a discharged capacitor that is charged during the measurement until the system reaches the open circuit condition. This tracer is capable of carrying out a number of successive measurements in a short period of time over a prolonged period for a range of different concentrator systems.

Direct radiation is measured by two pyrheliometers (Middleton DN5) installed in two independent trackers. Back plate temperature – or 'module temperature', to adhere to flat PV nomenclature – is measured with several thermal sensors on the back part of the module behind the cell. The cell temperature can then be calculated by adding the thermal drop caused by the thermal resistance of the elements between the back plate and the cell, information available from the manufacturer. Wind conditions are measured using a 3m-high anemometer, while the ambient temperature is measured with a thermal sensor Young model 41003, with multiplate radiation shield.

All measurements were taken between the months of January and May 2009 in Puertollano, Spain. Two further measurements taken in August 2008 and October 2008 were also studied for comparison purposes. Care was taken to ensure that all measurements were taken over a short period of time in order to ensure uniformity of local conditions for each set of measurements. While every effort will be made to use these measurements to calculate the nominal power under the standard conditions, the ISFOC standard conditions were also taken into account for comparison purposes, and are as follows: DNI = 850W/m^2; Equivalent cell temperature = 60°C; wind speed lower than 3.3m/s.

Standard method results

The first task is the translation of the PV table of conditions to a set of parameters for CPV. Radiation should be taken as direct normal radiation rather than global radiation, given that it is being applied to CPV. Following an analysis of data of the direct normal radiation in Puertollano between the months of January and April, the results were assimilated and are presented in Figs. 1 and 2.

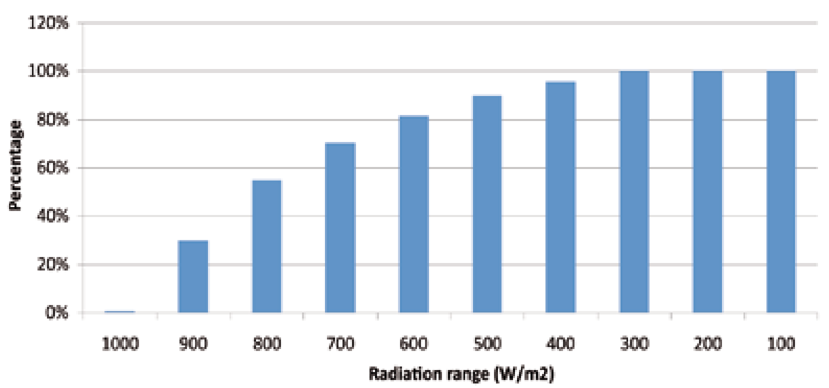

Figure 2. Frequency (%) of DNI values for which the radiation is larger than the abscise value in Puertollano between January and April 2009.

Irrad.	Air Mass	Module temperature			
		15°C	25°C	50°C	75°C
1100	AM1.5				
1000	AM1.5				
800	AM1.5				
600	AM1.5				
400	AM1.5				
200	AM1.5				

Table 2. Shaded set of parameters that could be filled for outdoor conditions in CPV.

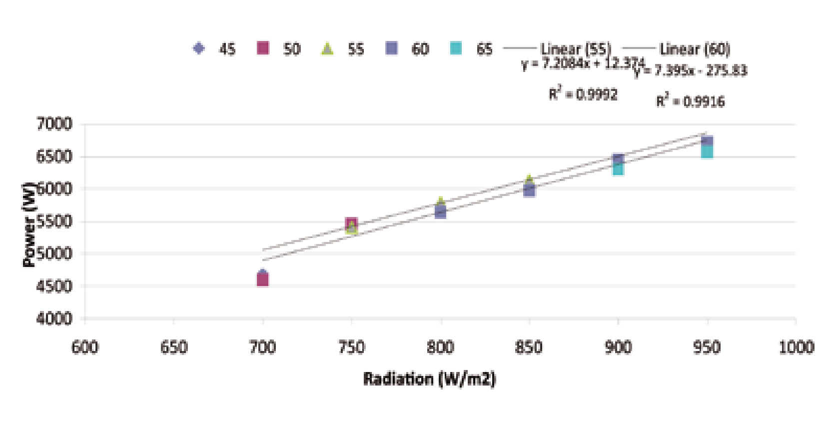

Figure 3. Power array output versus radiation at different levels of temperature.

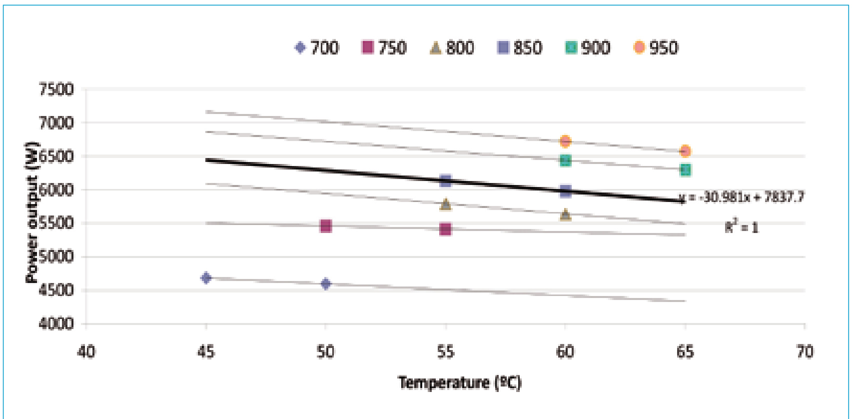

Figure 4. Array power output versus temperature at different levels of radiation.

Data was collected using ISFOC's meteorological station, which collects measurements every day at one-minute intervals.

Fig. 1 shows that 50% of the days in Puertollano during the months of January and April have more than 930W/m² as maximum DNI, while the data in Fig. 2 suggests that this figure was higher than 700W/m² 70% of the time. The values rarely dip below 400W/m². For this reason, only data above 700W/m² is considered as it is typical in CPV standards, because is very unusual to obtain stable data below this value.

Data collected over 15 days from two concentrators was used in this study. Module temperatures were always between 45°C and 75°C, depending of the radiation and ambient temperature.

Had it been necessary to fill Table 1 with real data at Air Mass 1.5, there would not have been sufficient values to fill the table. Therefore data with different air mass values was included, as any 'geometric' value of AM1.5 does not assure the standard or the same spectrum value.

With these measured values, it can be assumed that Table 1 in its entirety could only be partially filled using data taken from outdoor conditions, as shown in Table 2.

To allow for a wider set of conditions, Table 3 features radiation values from 700W/m² to 950W/m² in increments

		Module temperature				
		45°C	50°C	55°C	60°C	65°C
DNI (W/m^2)	700					
	750					
	800					
	850					
	900					
	950					

Table 3. Data log allowing for CPV conditions range.

		Module temperature				
		45°C	50°C	55°C	60°C	65°C
DNI (W/m^2)	700	4682.32	4595.53			
	750		5457.54	5412.90		
	800			5790.69	5640.25	
	850			6133.74	5978.84	
	900				6441.65	6301.33
	950				6718.48	6570.15

Table 4. Array power output in Watts for a set of values of radiation (W/m^2) and temperature (°C).

Concentrator A						
Date	B(W/m^2)	Tplate(°C)	Tcell(°C)	Pmeas(W)	Pcal(W)	Diff
18/02/2009	928.29	61.24	79.31	6515.98	6123.58	0.39%
05/05/2009	927	62.48	81.02	6514.20	6138.28	0.63%
25/03/2009	774.88	58.88	74.16	5887.84	6022.90	-1.26%
08/10/2008	824.34	54.24	70.73	5784.91	6051.33	-0.80%

Table 5. Calculated power using ISFOC's method for different conditions for concentrator A.

Concentrator B						
Date	B(W/m^2)	Tplate(°C)	Tcell(°C)	Pmeas(W)	Pcal(W)	Diff
26/02/2009	894.54	57.34	74.03	5821.61	6037.21	-1.03%
03/04/2009	908.52	53.40	71.53	6530.96	6216.42	1.91%
21/08/2009	917.69	67.55	85.91	6409.11	6151.11	-0.84%

Table 6. Calculated power using ISFOC's method for different conditions for concentrator B.

of $50W/m^2$, while module temperatures between 45 and 70°C are logged in 5°C increments. After four months of measurements, only a small portion of the data needed for the table was available because low values of temperatures with high radiation or high temperatures for low radiation did not occur.

Representing power versus radiation level, the linear regression of the power for each set of module temperatures is shown in Fig. 3.

With the available data, only regression lines were obtained for 55°C and 60°C back plate module temperature. The output power is then calculated at $850W/m^2$ and back plate at 60°C, obtaining P0 = 6005.67W. Power represented versus temperature yields the data in Fig. 4.

The regression lines show a great dispersion in slopes, which correspond to unusual values of the power to temperature relationship for multijunction cells. The reason for such dispersion is because there are only two data sets for each regression line, resulting in inaccurate results. For reasons of comparison, taking the $850W/m^2$ line and 44°C for the module back plate, which is equivalent to 60°C at the cell (like the ISFOC standard condition), then the output power is P_0=6474.536W. This result means that the calculated value is 6% higher than the nominal one.

ISFOC methodology: technical specifications

Again, for comparison reasons, the ISFOC methodology was also applied to this set-up, and was adapted to the outdoor measurements in order to analyze the data obtained during these measurements.

The ISFOC procedure for concentrator rating has been described in several papers [2,5] and is used by the company for acceptance of CPV power plants [6]. It is based on a set of measurements taken over a short period of time, which are then translated to the standard conditions with equations based on the Shockley model. The standard conditions for concentrator characterisation are defined at $850W/m^2$ and 60°C of cell temperature.

The measurement conditions are established as follows:

- The sky around the sun should not be cloudy during the measurement.
- The direct radiation should be higher than $700W/m^2$.
- The wind speed should be lower than 3.33m/s.

In order to determine the DC Power of the concentrator, the following variables are monitored during the measurements:

- The I-V curve of the system is measured with a capacitive charge, as described before.
- Direct radiation is measured by two pyrheliometers.
- Back plate temperature is measured with several thermal sensors on the back part of the module behind the cell.
- For this method it is necessary to know the internal thermal resistance between the cell and the back plate. Applying Equation 1 will yield the operating cell temperature from the actual measured back plate temperature.

$$T_{cell} = T_{b-s} + B \times R_{cell-back} \quad (1)$$

- Wind conditions – speed and direction – are also measured in order to determine their effect on the final rating in the future.
- The current and voltage values are then translated to as-defined standard test conditions following Equations 2 and 3, deduced from the Shockley equation model.

$$I_2 = I_1 \frac{B_{oper}}{B_{mea}} \quad (2)$$

Where

I_2	Standard test conditions current
I_1	Measured current
B_{mea}	Measured direct beam radiation
B_{oper}	Standard test conditions direct beam radiation

Where

N	Number of cells in series connection
IL_{meaj}	Short-circuit current of each junction
E_{gj}	Band gap of each junction
V_{oc}	System open circuit voltage
T_{oper}	Standard test conditions cell temperature
T_{cell}	Measured cell temperature

This method allows the calculation of DC power of the concentrator using only a set of few representative measurements in controlled conditions. Data obtained on the same days has been used to perform the calculation in line with the ISFOC procedure, together with some other previous measurements.

$$(3)\quad V_2 = V_1 + N \times \frac{0.0257 \times (T_{oper} - T_{cell})}{297} \times \ln\left(\frac{(I_{Lmea1} - I_i) \times (I_{Lmea2} - I_i) \times (I_{Lmea3} - I_i)}{I_{Lmea1} \times I_{Lmea2} \times I_{Lmea3}} \right) + \left(N \times (E_{g1} + E_{g2} + E_{g3}) - V_{OCmed} \right) \times \left(1 - \frac{T_{oper}}{T_{cel}} \right)$$

		Module temperature				
		45°C	50°C	55°C	60°C	65°C
DNI (W/m²)	700	5061.53	5029.17			
	750		5381.46	5346.80		
	800			5695.86	5658.88	
	850			6043.99	6004.70	
	900				6349.60	6308.00
	950				6693.57	6649.66

Table 7. Power measured at 927W/m² translated to the ISFOC set of conditions.

		Module temperature				
		45°C	50°C	55°C	60°C	65°C
DNI (W/m²)	700	8.10%	9.44%			
	750		-1.39%	-1.22%		
	800			-1.64%	0.33%	
	850			-1.46%	0.43%	
	900				-1.43%	0.11%
	950				-0.37%	1.21%

Table 8. Range of error between translated and measured values.

Concentrator B						
	Day	Time	Air mass	Rad+Temp	Radiation (W/m²)	Temp mod (°C)
1	03-abr	11:30	1.36	HRLT	905.303	54.607
2	21-ago	14:30	1.18	HRLT	919.4	68.42
3	23-feb	11:26	1.86	LRLT	800.555	58.321
4	23-feb	15:00	1.733	LRHT	800.699	62.34

Table 9. Set of measurements chosen for the bilinear interpolation method.

Only one set of parameters from these days with stable radiation and temperature was taken into account, resulting in the data shown in Tables 5 and 6.

It is clear from these data sets that the results are very close to the nominal power, with maximum error of 1.91%. The validity of this method has been tested with different concentrators, different ambient conditions and on different days of the year. This methodology will be proposed to the IEC Committee as a technical specification for plants' acceptance.

These equations can also be used to fill theoretically the table with the CPV set of conditions shown in Table 3. Translating one of the curves measured at 927W/m² and 62.8°C to the CPV conditions, the data in Table 7 is obtained.

Calculating the error of this translation versus the real measurements is calculated results in the data shown in Table 8.

From this data set, it can be seen that the errors between the theoretical translated values and the measured ones, except for the values of very low direct radiation, are lower than 1.5%. These results demonstrate the quality performance of ISFOC's equations in calculating power at different conditions, and could even be used in the future to fill the entire table of conditions.

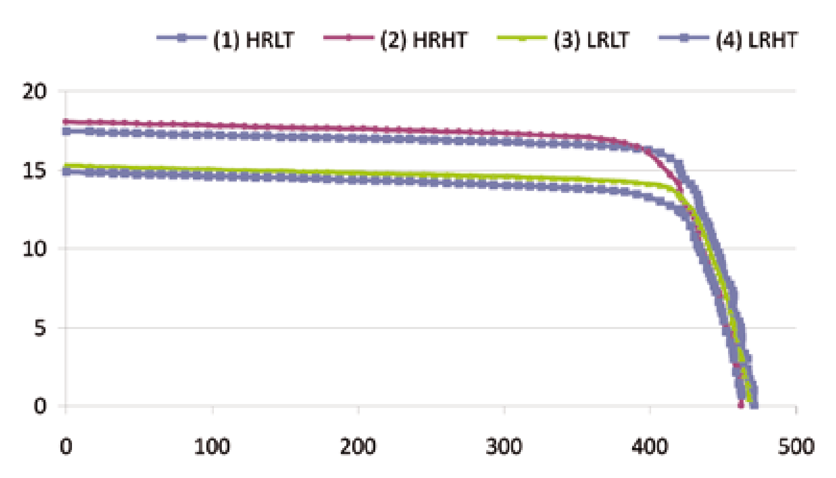

Figure 5. I-V curves of the four sets of chosen measurements.

Other methods

ISFOC has analyzed other rating procedures for comparison purposes.

Bilinear interpolation

As it is very difficult to obtain data at various different conditions in order to perform the study of interpolation or regression, the methodology of bilinear interpolation as described by Bill Marion for flat modules [7] was applied in this case. This procedure requires only four I-V curves in different conditions:

- High radiation and low temperature HRLT
- High radiation and high temperature HRHT
- Low radiation and low temperature LRLT
- Low radiation and high temperature LRHT.

Using ISFOC's accumulated data, it was found to be difficult to achieve such conditions and consequently the four required curves, especially with a fixed Air Mass = 1.5. This difficulty is because the real CPV working conditions are, in fact, very narrow. Therefore, different air mass conditions were employed – in every case below AM 2 – to fill the four cases, using the data shown in Table 9. The four I-V curves of concentrator B are represented in Fig. 5.

This procedure requires the translation of curve 1 and 2 to curve 5, and curves 3 and 4 to curve 6, using Equations 4-11. Once curves 5 and 6 have been established, the final translated curve 7 is obtained using Equations 12 and 13, shown in Fig. 6.

The final power value calculated with this method is P_0=6000.8847W at 850W/m² and 60°C of module (back plate) temperature. Attempting these calculations at 44°C module temperature (to be close to the 60°C cell temperature of the ISFOC standard conditions), the translation does not work properly because all the curves are translated to a lower temperature and a higher V_{oc}, yielding inaccurate results.

The power calculated with this methodology for the ISFOC standard conditions is P_0=5616.638W – almost 8% less than the nominal power value.

$$I_{SC} = \frac{E}{E_1} \cdot I_{SC(1)} \cdot [1 + \alpha \cdot (T - T_1)] \quad (4)$$

$$V_{OC} = V_{OC(1)} \cdot [1 + \beta \cdot (T - T_1)] \cdot \left[1 + (m \cdot T + b) \cdot \ln \frac{E}{E_1}\right] \quad (5)$$

$$\alpha = \left(\frac{I_{SC(2)} \cdot E_1}{I_{SC(1)} \cdot E_2} - 1\right) / (T_2 - T_1) \quad (6)$$

$$F(\beta, m, b) = [1 + \beta \cdot (T - T_1)] \cdot \left[1 + (m \cdot T + b) \cdot \ln\left(\frac{E}{E_1}\right)\right] - \frac{V_{OC}}{V_{OC(1)}} = 0 \quad (7)$$

$$I_5 = I_1 = I_2' \quad (8)$$

$$V_5 = V_1 + \frac{(V_2' - V_1)(V_{OC(5)} - V_{OC(1)})}{(V_{OC(2)'} - V_{OC(1)})} \quad (9)$$

$$I_6 = I_3 = I_4' \quad (10)$$

$$V_6 = V_3 + \frac{(V_4' - V_3)(V_{OC(6)} - V_{OC(3)})}{(V_{OC(4)'} - V_{OC(3)})} \quad (11)$$

$$V_7 = V_5 = V_6 \quad (12)$$

$$I_7 = I_6 + \frac{(I_5 - I_6)(I_{SC(7)} - I_{SC(6)})}{(I_{SC(5)'} - I_{SC(6)})} \quad (13)$$

Regression methodology

Regression methodology is based on the American Standard Test Method for "Rating Electrical Performance of Concentrator Terrestrial Photovoltaic Modules and Systems under Natural Sunlight" ASTM E 2527-06 [8]. This method, which has been used in the U.S. for several years, involves the determination of the performance of a CPV system by measuring the maximum power over a wide range of irradiance, air temperature and wind values.

A multiple linear regression is used to rate the maximum power at standard concentrator reporting conditions, defined as T_0 = 20ºC; v_0 = 4m/s; E_0 = 850W/m^2, where E is the direct solar irradiance; T_a is the air temperature; v is the wind speed and P is the maximum power.

The calculation of the results is carried out by computing the regression coefficients a_1, a_2, a_3 and a_4 by performing a multiple linear regression of P as a function of E, v and T_a using Equation 14.

$$P = E \cdot (a_1 + a_2 \cdot E + a_3 \cdot T_a + a_4 \cdot v) \quad (14)$$

In order to calculate the nominal power of the system, the value of P_0 is determined by substituting the values of T_0, v_0, E_0, and the calculated values of a_1, a_2, a_3 and a_4 in Equation 15.

$$P_0 = E_0 \cdot (a_1 + a_2 \cdot E_0 + a_3 \cdot T_0 + a_4 \cdot v_0) \quad (15)$$

The same data as was used for the interpolation methods has been used to carry out the regression, which means that there are seven days of data available for each concentrator. Prior to carrying out the calculations, the data was filtered for radiation higher than 700W/m^2 with a variation lower than 0.4% every minute.

	Regression coefficients
a1	7.260300387
a2	-0.000547589
a3	0.007266881
a4	0.029880332

Table 10. Regression coefficients using data collected over five days.

The wind should not have variations higher than 5m/s every five minutes, which is not likely to pose any problems in Puertollano.

The results of the linear regression are clearly dependent on the amount of data used as

including only one day's data does not yield representative results. The calculated power for one day's data is P_0= 5518,8042W at the nominal conditions (T_0 = 20ºC, v_0 = 4m/s, E_0 = 850W/m^2); three days' data results in calculated power of P_0 = 5988.8745W; while five days' data yields a power value of P_0 = 6000.7523W at standard conditions. The regression coefficients are shown in Table 10.

Using this method with the ISFOC standard conditions, an ambient temperature of 10ºC ambient temperature needs to be forced in order to make the cell temperature as close to 60ºC as possible. With this temperature and 3.3m/s wind speed, a power value of P_0 = 5921.20W is obtained, 3% smaller than the nominal value.

Methods comparison, summary and conclusions

Table 11 illustrates the final data of the array power output at standard conditions of DNI = 850W/m^2, cell temperature = 60ºC and wind lower than 3.3 m/s for an entire concentrator system.

On comparison of all the aforementioned rating procedures, it must be noted that these results are not definitive as they are derived from only four months of measurements in one location using only two concentrators. Futures studies will confirm the validity of these first results.

Secondly, it must also be stressed that that some of the methods mentioned here were developed for modules and indoor measurements and, contrarily, these procedures were applied to entire systems and outdoor measurements under real conditions.

	Power in STC conditions (W)	Diff
Nominal Power	6100.000	0.00%
PV method	6474.536	6.14%
Bilinear interpolation	5616.638	-7.92%
Regression method	5921.205	-2.93%
ISFOC worst case	6216.420	1.91%

Table 11. Array power output of the different procedures in ISFOC standard conditions (DNI = 850 W/m², cell temperature = 60ºC and wind lower than 3.3 m/s) vs. nominal power.

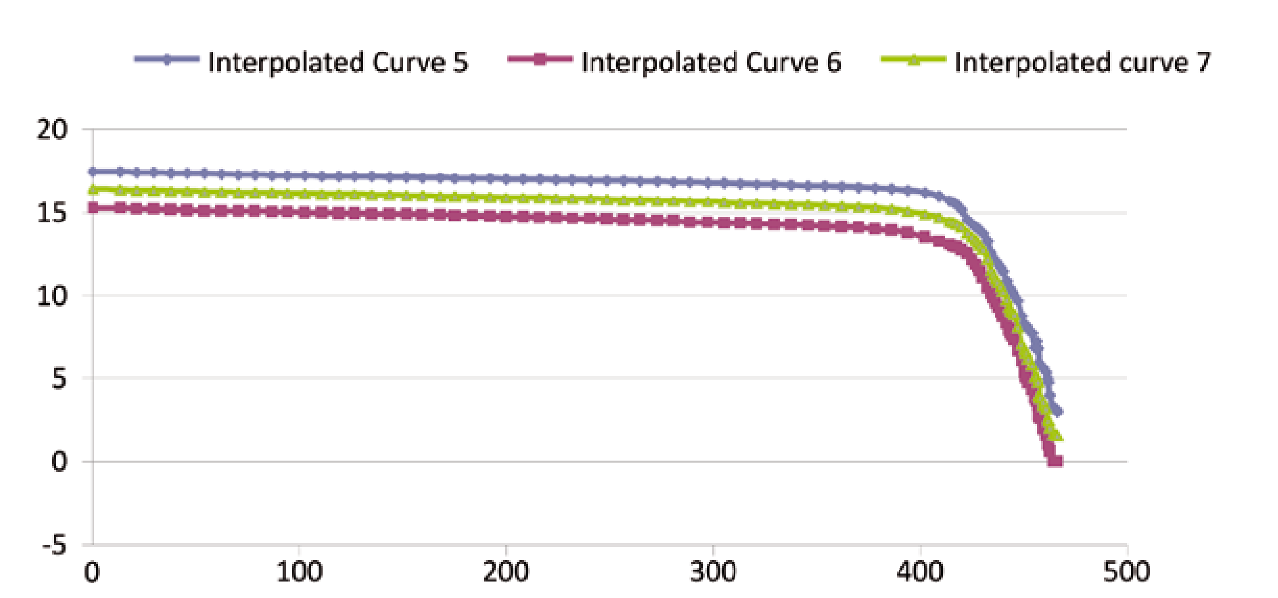

Figure 6. Translated and interpolated curves 5, 6 and 7, achieved using the bilinear interpolation method.

Following this study of the different methodologies, it can be concluded that:

- The first method based on the PV standard needs several days to perform the measurements requires for the data table, and even so, not all of the required measurements have been obtained in this case. The procedure to obtain the data under the condition of shading and light filtering is not feasible for a whole concentrator. New procedures for indoor and outdoor conditions need to be developed for this new standard proposal.
- The method of bilinear interpolation also needs many different measurements, taken at different times of the year, as well as intensive calculations.
- The regression methodology needs at least three to five days to ensure good results. The final coefficients do not necessarily have a physical interpretation as shown previously.

The ISFOC method has proven that with only a few measurements in the given measurement conditions and with only one simple calculation, the results are repetitive and stable, even at different times of the year. The narrow operating conditions of CPV systems allow a good stability for corrections.

Conclusions

The procedure chosen by the IEC Committee as the international standard for power rating is that based on the flat PV power rating defined with a different set of conditions. Therefore all efforts need to be focused on the development of measurement procedures under this set of conditions.

As this paper has demonstrated, the CPV set of parameters needs to be reduced to the narrow operating conditions of the CPV systems. Measuring the entire set of conditions under real conditions is very difficult in many locations. Therefore, a new procedure for outdoor conditions measurement need to be set but, more importantly, there is now an opportunity to develop new solar simulators and standards to carry out this procedure under indoor conditions.

ISFOC's procedure will be used as an international technical specifications reference for acceptation plants. Furthermore, the equations could even be used as a way to obtain the theoretical values for the entire set of measurement conditions.

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About the Authors

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