Performance of a concentrating photovoltaic monomodule under real operating conditions: Part II – Power rating

Marios Theristis[1,*], Eduardo F. Fernández[2], George E. Georghiou[1], and Tadhg S. O'Donovan[3]

[1] PV Technology Laboratory, FOSS Research Centre for Sustainable Energy, Department of Electrical and Computer Engineering, University of Cyprus, Nicosia, 1678, Cyprus
[2] Centre for Advanced Studies in Energy and Environment (CEAEMA), IDEA Solar Energy Research Group, Electronics and Automation Engineering Department, University of Jaén, Las Lagunillas Campus, Jaén, 23071, Spain
[3] Institute of Mechanical, Process and Energy Engineering, Heriot-Watt University, Edinburgh, EH14 4AS, UK

* corresponding author email: theristis.marios@ucy.ac.cy

Abstract — In Part I of this work, a comprehensive outdoor characterisation of a concentrating photovoltaic monomodule was presented where the importance of atmospheric parameters on the performance of such systems was highlighted. In this work, Part II, the power ratings of a concentrating photovoltaic monomodule are determined using different methods and filtering criteria that account for the spectrum. Spectral variations are considered to be a major parameter that contributes to the uncertainty of concentrating photovoltaic power ratings due to the dynamic behaviour of outdoor conditions. In order to address the sensitivity of such variations, Concentrator Standard Operating Conditions (CSOC) and Concentrator Standard Test Conditions (CSTC) power rating estimations are performed using different scenarios and compared with measurements obtained using a Helios 3198 solar simulator. The application of different methods and filtering criteria, in terms of the spectral matching ratio (*SMR*) of the middle to bottom subcell, exhibits differences of up to 3.64% and 1.37% for the CSOC and CSTC estimations respectively. The comparison with the CSTC power rating obtained indoors shows a difference of up to 8.45%; this is attributed to the tracking errors and also the temperature dependence of the refractive optics. The application of the spectral factor (*SF*) as filtering criterion reduces the CSTC power rating difference to 6.74% compared to the corresponding value obtained indoors. In addition, the CSOC power rating estimation using the *SF* filtering exhibits similar results to the standardised procedure using the *SMR* indices (within 1.21%).

Keywords — concentrating photovoltaic, III-V multijunction solar cells, power rating, spectral indices, solar simulator

1. Introduction

The rating procedures of photovoltaic (PV) devices and modules are important for the comparison of the technologies [1]. Concentrating photovoltaic (CPV) modules can be either rated indoors or outdoors (by translating outdoor current-voltage, *I-V*, measurements to Concentrator Standard Test Conditions [2]) under CSTC (i.e. reference direct spectrum of air mass AM1.5D according to the American Society for Testing and Materials, ASTM G173-03[3], direct normal irradiance, $DNI = 1000\ W/m^2$ and cell temperature, $T_{cell} = 25°C$) or outdoors under Concentrator Standard Operating Conditions, CSOC, (i.e. AM1.5D, $DNI = 900\ W/m^2$, ambient temperature, $T_{amb} = 20°C$ and wind speed, $WS = 2$ m/s). The CSOC and CSTC power ratings are currently determined according to the recently published International Electrotechnical Commission (IEC) 62670-01 [4] (Concentrator Photovoltaic (CPV) Performance Testing - Standard Conditions) and IEC 62670-3 [5] (Concentrator Photovoltaic (CPV) Performance Testing - Performance Measurements and Power Rating) [6]. Both CSOC and CSTC must be consistent with the AM1.5D spectral irradiance described in IEC 60904-3 [7].

Prior to the publication of the IEC 62670, the CSOC power rating was evaluated using the multiple regression equation of power from ASTM E2527-09 [8] as a function of *DNI*, T_{amb} and *WS*. However, since the publication of IEC 62670-3, the CSOC power determination follows a different methodology. Since many test laboratories do not have an appropriate solar simulator for CSTC measurements, this power rating can also be determined by the translation of outdoor measurements according to the method described by Muller *et al.* [2] and published in the final version of IEC 62670-3 [5]. Since indoor CSTC power rating is obtained under a controlled environment, while the outdoor characterisations are subject to variable ambient and atmospheric conditions [9], additional uncertainties and deviations from the real CSTC power determination can occur. Such uncertainties or deviations might be caused by passing clouds [10], spectrum [11] and temperature [12] variations amongst others. In order to match the spectrum conditions with the reference, a number of filtering criteria, based on the spectral matching ratio (*SMR*) [13], are recommended to be applied on the measured data. However, although the ranges of *SMR* filters are given in IEC 62670-3, they were under a significant debate within the IEC subgroup [2] due to the fact that "tight" ranges of *SMR* might limit the number of available datapoints, especially at locations where the reference conditions are not met frequently. Therefore, the sensitivity of the spectral filtering criteria on the CSTC power determination needs to be further examined. In addition, it is also important to investigate the CSOC power ratings obtained using the newly developed standard against the methods reported in the past.

In order to examine these issues, a comprehensive outdoor characterisation needs to be undertaken where the electrical and spectral characteristics of a CPV module are analysed based on atmospheric, irradiance and meteorological variations. This was the subject of Part I of this work [14] where the results of a CPV monomodule highlighted the importance of considering the influence of the atmospheric parameters on the performance of such technologies. The advantage of using a monomodule rather than a full module is that mismatch losses along cells are neglected [15]. The detailed information obtained from the outdoor characterisation are fundamental to the better understanding of the behaviour of this technology [16] and can provide valuable knowledge of the possible deviations within the power rating procedures. The aim of Part II is to apply both the indoor and outdoor power rating procedures on a CPV monomodule according to IEC 62670-3 [5] and compare the obtained results against the ratings determined by other methods that were reported in the past. In addition, different spectral filtering criteria are applied and deviations within the power rating determinations are examined in order to investigate the influence of the range of spectral filters along with their possible effects. Furthermore, an alternative but widely used spectral index (i.e. the spectral factor, *SF*) [17], is applied on the IEC 62670-3 filtering procedure to examine its applicability in obtaining reasonable CSTC and CSOC power ratings.

2. Indoor characterisation for CSTC power rating

The CPV monomodule (Suncore DDM-1090×) was tested under laboratory (controlled) conditions in order to compare the indoor power rating against the corresponding CSTC rating obtained outdoors by translating *I-V* measurements taken on sun. This is useful to compare both power rating approaches, indoors and outdoors, as well as to better analyse the results presented in the next sections. The system was measured with the multi-flash Helios 3198 pulse solar simulator [18] at the Centre for Advanced Studies in Energy and Environment (CEAEMA) of the University of Jaén. This simulator (see Figure 1) uses a Xenon flash lamp for generating the solar radiation and a parabolic mirror as a collimator. The spectral irradiance distribution is close to the AM1.5D reference spectrum and the collimation angle is approximately ±0.3° which, according to IEC 67670-3, is appropriate for this monomodule's acceptance angle of ±0.7° (i.e. the collimation angle must be at least 10% less than the device's acceptance angle and greater than ±0.26°). It is worth mentioning, that besides the collimation angle, this simulator meets the requirements defined in IEC 62670-3 for the indoor determination of the electrical characteristics of multijunction (MJ) CPV modules [19]. Hence, it represents a powerful set-up for the electrical characterisation of CPV modules and systems under fully controlled conditions.

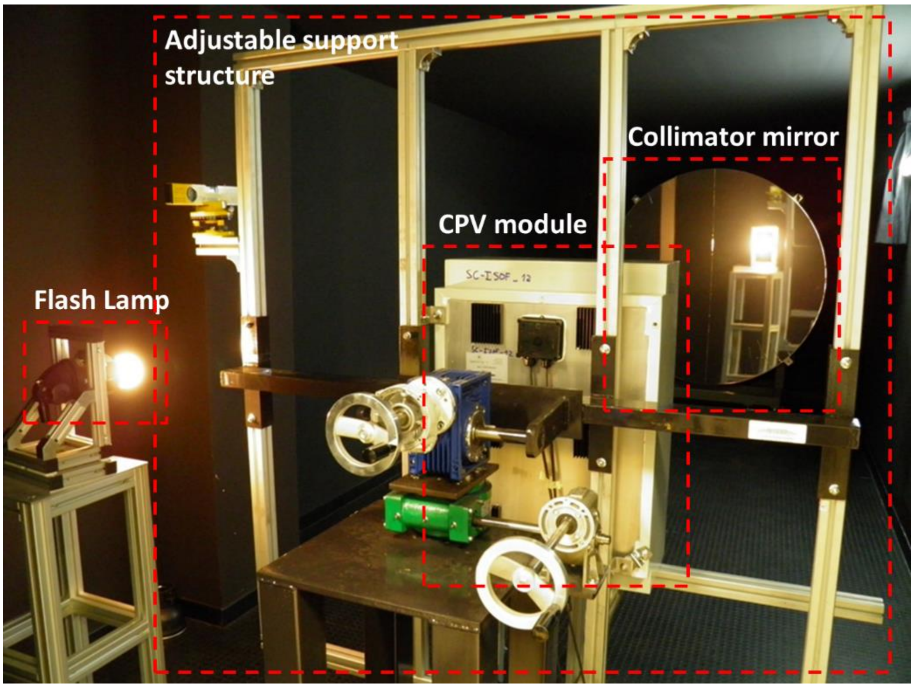

Figure 1: Photograph and main components of the multi-flash Helios 3198 CPV pulse solar simulator at the CEAEMA of the University of Jaén.

The indoor characterisation followed the same procedure as the one presented by Fernández *et al.* [20]. Initially, the monomodule was placed on the support structure of the solar simulator. The primary optical element, i.e. a Fresnel lens, was cleaned and examined to avoid any distortion of the data caused by soiling or damaged optical elements. The module was then aligned to the continuous light, a halogen lamp located in the centre of the Xenon flash tube, by changing the azimuth and elevation angles of the adjustable support structure in order to maximize the light harvested by the system. The spectrum was evaluated with component solar cells using the *SMR* indices as criteria, according to IEC 62670-3. The *SMR* indices were explained in Part I of this work. Finally, the *I-V* curve of the monomodule was measured at CSTC conditions by fixing the input irradiance and room temperature at 1000 W/m^2 and 25°C respectively. The rated values of the main electrical parameters of the monomodule (i.e. short-circuit current, I_{sc}, current at maximum power, I_{mp}, open-circuit voltage, V_{oc}, voltage at maximum power, V_{mp}, and maximum power, P_{mp}, and efficiency, η) as measured with the solar simulator are given in Table 1. The *I-V* curve of the module at the same rated conditions is also shown in Figure 2.

Parameter	Value
I_{sc} (A)	11.65
I_{mp} (A)	11.27
V_{oc} (V)	3.21
V_{mp} (V)	2.45
P_{mp} (W)	27.62
η (%)	25.30

Table 1: Rated values of the main electrical parameters of the Suncore DDM-1090× monomodule obtained with the Helios 3198 CPV solar simulator at the CEAEMA of the University of Jaén at 1000 W/m^2, spectral irradiance equivalent to AM1.5D reference spectrum and room temperature of 25ºC ± 0.5ºC.

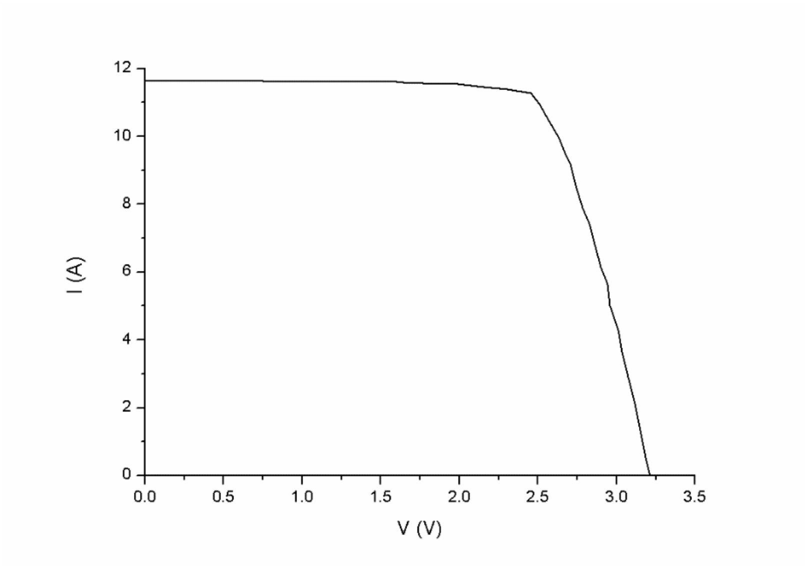

Figure 2: Current-voltage curve of the of the Suncore DDM-1090× monomodule obtained with the Helios 3198 CPV solar simulator at the CEAEMA of the University of Jaén at 1000 W/m^2, spectral irradiance equivalent to AM1.5D reference spectrum and room temperature of 25ºC ± 0.5ºC.

3. Data filtering and outdoor power rating procedures

In order to achieve repeatable power rating determinations, various filtering criteria are required by IEC 62670-3; these are given in Table 2, where *GNI* is the global normal irradiance.

The criteria ensure stability on the outdoor conditions while extreme ambient conditions are excluded. Filters regarding the tracker's accuracy are also included.

Filtering parameter	**Acceptable range**
DNI	700 - 1100 W/m^2
DNI/*GNI*	> 0.8
10 min *DNI* variation prior to *I-V* curve	< 10%
30 min *DNI* variation prior to *I-V* curve	< 40%
DNI variation during *I-V* sweep	< 1%
All *SMR* indices	within 3% of unity*
Instantaneous azimuth pointing error	< 0.2 times the acceptance angle
Instantaneous elevation pointing error	< 0.2 times the acceptance angle
T_{amb}	0 - 40°C
5 min average *WS*	0.5 - 5 m/s

***If only two subcells are current limiting the device, the *SMR* between both subcells should be within 1% of unity.**

Table 2: Filtering criteria for CSOC and CSTC power ratings as per the IEC 62670-03 [5].

The power rating procedures require knowledge of the cell temperature (T_{cell}). However, the measurement of T_{cell} is not a trivial procedure because a temperature sensor cannot be placed at the rear surface of the solar cell without damaging the receiver, nor can it be placed in the path of the concentrated sunlight because the measured temperature would be much higher than the real one [21]. For this reason, indirect methods need to be applied. According to IEC 62670-03, the I_{sc}-V_{oc} method is used as follows:

$$T_{cell} = \frac{V_{oc} - V_{oc,ref} + \beta_{Voc,ref} \cdot T_{cell,ref}}{N_s \cdot \left(\frac{n \cdot k_B}{q} \right) \cdot \ln\left(\frac{I_{sc}}{I_{sc,ref}} \right) + \beta_{Voc,ref}} \quad \textbf{(1)}$$

where β_{Voc} is the temperature coefficient of open-circuit voltage obtained using the thermal transient method (TTM) described by Muller *et al*. [2], N_s is the number of cells connected in series inside the module, n is the diode ideality factor, k_B is the Boltzmann constant and q is the elementary charge. The subscript "ref" indicates the reference values.

3.1. CSTC power determination according to IEC 62670-3

In order to calculate the nominal power at CSTC conditions (P_{CSTC}), equations (2) to (4) need to be used. Equation (2) is a relative factor that has been proposed for the intensity correction of voltage [2]:

$$f_{V_{OC},CSTC} = 1 - \frac{N_S \cdot n \cdot k_B \cdot T_{cell}}{q \cdot V_{oc,meas}} \ln\left(\frac{DNI}{1000}\right) \quad \textbf{(2)}$$

This factor is then used for the efficiency calculation under CSTC [2]:

$$\eta_{\mathrm{mod},CSTC} = f_{V_{oc},CSTC} \cdot \left(\eta_{\mathrm{mod},meas} - \delta \cdot \left(T_{cell} - T_{cell,ref}\right)\right) \quad \textbf{(3)}$$

where $\eta_{mod,meas}$ is the measured efficiency and δ is the efficiency's temperature coefficient which is also obtained using the TTM. Therefore, the P_{CSTC} can be then calculated by:

$$P_{CSTC} = 1000 \cdot \eta_{CSTC,avg} \cdot Aperture \quad \textbf{(4)}$$

3.2. CSOC power determination according to IEC 62670-3

IEC 62670-3 explicitly describes the procedure to obtain the CSOC power rating (P_{CSOC}). In order to achieve this, a temperature correction based on DNI and an additional intensity correction for the voltage need to be applied, respectively, as follow:

$$f_{DNI} = average\left(\frac{T_{cell,i} - T_{amb,i}}{DNI_i}\right) \quad \textbf{(5)}$$

and

$$f_{V_{OC},CSOC} = 1 + \frac{N_S \cdot n \cdot k_B \cdot T_{cell}}{q \cdot V_{oc,meas}} \ln\left(\frac{900}{DNI}\right) \quad \textbf{(6)}$$

Hence, the CSOC efficiency can be calculated by:

$$\eta_{\mathrm{mod},CSOC} = f_{V_{oc},CSOC} \cdot \left[\eta_{\mathrm{mod},meas} - \delta \cdot \left\{ \left(T_{amb,i} - 20 \right) + f_{DNI} \cdot \left(DNI_{i-900} \right) \right\} \right] \quad \textbf{(7)}$$

and finally the P_{CSOC} is estimated using:

$$P_{CSOC} = 900 \cdot \eta_{CSOC,avg} \cdot Aperture \quad \textbf{(8)}$$

3.3. CSOC power determination according to ASTM E2527-09

As mentioned in the introduction, IEC 62670-3 was released recently. Prior, to its publication, other procedures for the CSOC power estimation were applied. In this analysis, the main methods are studied based on the extensive experimental campaign that was performed and described in Part I of this work. The ASTM E2527-09 [8] uses a simple equation to calculate the P_{CSOC}:

$$P_{CSOC} = DNI \cdot \left(\alpha_1 + \alpha_2 \cdot DNI + \alpha_3 \cdot T_{amb} + \alpha_4 \cdot WS \right) \quad \textbf{(9)}$$

where the coefficients α_1 to α_4 are calculated using regression analysis on outdoor measurements. As can be seen, the spectral dependence is not taken into consideration in ASTM E2527-09. This method is more straightforward compared to IEC 62670-3 since the P_{CSOC} can be easily determined by regression without necessarily requiring expensive equipment that account for the spectrum.

3.4. CSOC power determination methods according to Steiner *et al*.

In addition to ASTM E2527-0 and IEC 62670-3, a P_{CSOC} equation was also suggested by Steiner *et al.* [6] using the "averaging method", is described by:

$$P_{CSOC} = \frac{\left(\sum_i P_i \cdot \frac{900}{DNI_i} \right)}{N} \quad \textbf{(10)}$$

where P is the measured power and N is the number of measurements. The "translation method" suggested by the same authors is the same as equation (10) with the DNI being multiplied (i.e. corrected) by the $SMR2$, so that the effect of precipitable water (PW) is considered:

$$P_{CSOC} = \frac{\left(\sum_i P_i \cdot \frac{900}{DNI_i \cdot SMR2} \right)}{N} \quad \textbf{(11)}$$

4. Power ratings determination of CPV monomodule based on IEC 62670-3

Following the filtering criteria and procedures described in Section 3, the DDM-1090× was rated using different spectral filters for the CSTC and CSOC power rating estimations. In addition, CSOC is also evaluated based on the procedures applied in the past.

4.1. CSTC power rating using different *SMR2* filters

As mentioned in Section 2, the CSTC can be evaluated using the method described by Muller *et al*. [2], i.e. by the translation of outdoor *I-V* measurements. According to IEC 62670-3, data from at least three different days need to be collected for a CSTC or CSOC translation. The $SMR1$ was considered to be $SMR1$ = 1±1% (following the IEC 62670-3 recommendation where two subcells are current matched) and the $SMR2$ was varied according to the ranges used by Fraunhofer Institute for Solar Energy Systems ($SMR2$ = 1±5%) [2], IEC 62670-3 ($SMR2$ = 1±3%) [5], National Renewable Energy Laboratory ($SMR2$ = 1±2.5%) [2] and Universidad Politécnica de Madrid ($SMR2$ = 1±1%) [22].

From the three-day dataset, out of 1735 datapoints, the data were reduced to 85, 61, 48, 45 with "tighter" $SMR2$ (i.e. 1±5%, 1±3%, 1±2.5%, 1±1% respectively), while with all measurements from 25/06/2015 to 21/08/2015, out of 14082 datapoints, the data were reduced to 224, 162, 146, 91 with "tighter" $SMR2$. The results of the CSTC power rating determinations are summarised in Tables 3 and 4 where the percentage differences of each estimation against the indoor CSTC power rating (i.e. $P_{CSTC,sim}$ = 27.62 W) obtained using a Helios 3198 solar simulator (presented in Section 2) are also given. It can be seen that the P_{CSTC} ranges from 25.38 W to 25.73 W, depending on the *SMR2* filter and the amount of data considered (after filtering). This translates to only 1.37% difference and can be concluded that three clear days of measurements can be adequate for the CSTC estimation, independently of the *SMR2* range although this might vary at other locations or for different CPV modules. Moreover, the maximum differences in the CSTC power rating estimations based on different spectral filtering ranges of *SMR2*, were found to be within 0.24% and 0.78% for the three and all days considered, respectively. It can therefore be concluded that the *SMR* range suggested by IEC 62670-3 is reasonable. When the outdoor P_{CSTC} estimation is compared with the $P_{CSTC,sim}$ however, the difference jumps up to 8.45% (see Tables 1 and 3) with a minimum of 7.09% when all measurements (after filtering) are taken into account and the *SMR2* filter is equal to 1±5%. It is also worth noting that the larger dataset including all measurements exhibited relatively lower differences (between 7.09% and 7.86), compared to the dataset of the three selected days (differences between 8.22% and 8.45%). Furthermore, the CSTC power rating method, according to IEC 62670-3 (i.e. filtering according to Table 2 and *SMR1* = 1±1%, *SMR2* = 1±3%) estimated a P_{CSTC} = 25.44 W and 25.55 W using the three-day dataset and all measurements respectively; these power values correspond to 8.22% and 7.79% difference, compared to the CSTC power rating obtained indoors. Finally, it can be observed that all methods underestimate the indoor CSTC power rating.

The relatively high differences can be attributed again (see also Part I of this work), to the effect of the Fresnel lens temperature since the indoor test is conducted using a flash solar simulator under controlled ambient temperature of 25°C; as such, the impact of the temperature dependence of the Fresnel lens is negligible. In addition, since the trackers present errors (even very low; see filtering criteria in Table 2), they may contribute to the magnitude of difference between indoors and outdoors CSTC power rating.

SMR2 Filter	$\eta_{CSTC,avg}$ (%)	P_{CSTC} (W)	Difference from $P_{CSTC,sim}$ (%)	No. of data
SMR2 = 1±5%	23.34	25.44	8.22	85
SMR2 = 1±3%*	23.34	25.44	8.22	61
SMR2 = 1±2.5%	23.28	25.38	8.45	48
SMR2 = 1±1%	23.29	25.38	8.45	45
Difference (%)	0.26	0.24	N/A	N/A

***indicates the spectral filtering according to the IEC 62670-3, i.e. *SMR1* = 1±1% and *SMR2* = 1±3%.**

Table 3: P_{CSTC} and $\eta_{CSTC,avg}$ estimations during the three selected days along with the number of remaining datapoints after filtering of *SMR2* and Table 2. The percentage difference indicates the difference between maximum and minimum values. $P_{CSTC,sim}$ refers to the indoor CSTC power rating obtained using a Helios 3198 solar simulator (i.e. 27.62 W, see Table 1).

***SMR2* Filter**	$\eta_{CSTC,avg}$ (%)	P_{CSTC} (W)	Difference from $P_{CSTC,sim}$ (%)	No. of data
SMR2 = 1±5%	23.60	25.73	7.09	224
SMR2 = 1±3%*	23.44	25.55	7.79	162
SMR2 = 1±2.5%	23.43	25.53	7.86	146
SMR2 = 1±1%	23.45	25.56	7.75	91
Difference (%)	0.72	0.78	N/A	N/A

***indicates the spectral filtering according to the IEC 62670-3, i.e. *SMR1* = 1±1% and *SMR2* = 1±3%.**

Table 4: P_{CSTC} and $\eta_{CSTC,avg}$ estimations for all measurements from 25/06/2015 to 21/08/2015 in Albuquerque, NM along with the number of remaining datapoints after filtering of *SMR2* and Table 2. The percentage difference indicates the difference between maximum and minimum values. $P_{CSTC,sim}$ refers to the indoor CSTC power rating obtained using a Helios 3198 solar simulator (i.e. 27.62 W, see Table 1).

4.2. CSOC power rating using different *SMR2* filters and methods

The methods described by equations (5) to (11) (i.e. IEC 62670-3, ASTM E2527-09 and Steiner *et al.*), were considered for the CSOC power rating estimations. The same filters as for the CSTC evaluation were applied, and the *SMR2* was varied in the same way for the three days described in Part I of this work and also for all measurements from 25/06/2015 to 21/08/2015 in Albuquerque, NM. It should be mentioned that ASTM E2527-09 and Steiner *et al.* do not apply the same filtering criteria in the corresponding power rating methods, however, in this analysis, the same filters are applied, according to IEC 62670-3, to allow a direct comparison of the methods.

The results of the CSOC power rating determinations are given in Tables 5 and 6 for the three relatively clear-sky days and also for all measurements respectively. In parenthesis the determination coefficients (R^2) of the regression method of ASTM E2527-09 are shown. In addition, the percentage differences between the minimum and maximum values of all methods and spectral filtering ranges are also given. In the case of the three clear-sky days, the P_{CSOC} range was found to vary from 20.74 W to 21.53 W between all methods and *SMR2* filters; this is a difference of 3.74%. When all measurements were considered, the P_{CSOC} range was found to vary from 21.08 W to 21.54 W, a maximum of 2.16% difference. By comparing the R^2 values of the ASTM E2527-09 method between the two scenarios, it can be seen that the larger dataset has a significantly lower R^2. In terms of the percentage difference between the four methods analysed, a maximum difference of 3.64% was found when the three-day dataset was used for *SMR2* = 1±5%. A minimum of 1.17% difference between methods was observed when a tight spectral filter was applied (i.e. *SMR2* = 1±1%) on the whole dataset between 25/06/2015 and 21/08/2015 (after filtering). In terms of the effect of spectral filtering, it is shown that the differences are adequate (within 1.77% for all methods whereas IEC 62670-3 is within 0.61%), therefore, similar to the case of the CSTC, the filtering criteria of IEC 62670-3 are reasonable. It also has to be noted that the range of differences (between 1.17% and 3.64%) for all methods and filtering criteria can be considered satisfactory. Furthermore, the CSOC power rating procedure according to IEC 62670-3 (i.e. filtering according to Table 2 and *SMR1* = 1±1%, *SMR2* = 1±3%) determined a $P_{CSOC,IEC62670}$ = 21.27 W and 21.40 W for the three-day dataset an all measurements respectively.

SMR2 Filter	Eq. (9)	Eq. (10)	Eq. (11)	IEC 62670-3	Difference (%)	No. of data
SMR2 = 1±5%	21.51 W (0.94)	20.97 W	20.74 W	21.23 W	3.64	85
SMR2 = 1±3%*	21.52 W (0.93)	21.05 W	20.99 W	21.27 W	2.49	61
SMR2 = 1±2.5%	21.49 W (0.93)	21.02 W	21.11 W	21.24 W	2.21	48
SMR2 = 1±1%	21.53 W (0.94)	21.01 W	21.09 W	21.24 W	2.44	45
Difference (%)	0.19	0.38	1.77	0.19	N/A	N/A

***indicates the spectral filtering according to the IEC 62670-3, i.e. *SMR1* = 1±1% and *SMR2* = 1±3%.**

Table 5: P_{CSOC} estimations during the three selected days using equations (5) to (11) along with the number of remaining datapoints after filtering of *SMR2* and Table 2. In parenthesis is the R^2 value of the regression. The percentage differences indicate the difference between maximum and minimum values.

SMR2 Filter	Eq. (9)	Eq. (10)	Eq. (11)	IEC 62670-3	Difference (%)	No. of data
SMR2 = 1±5%	21.32 W (0.81)	21.22 W	21.08 W	21.53 W	2.11	224
SMR2 = 1±3%*	21.49 W (0.73)	21.11 W	21.23 W	21.40 W	1.78	162
SMR2 = 1±2.5%	21.54 W (0.73)	21.11 W	21.30 W	21.40 W	2.02	146
SMR2 = 1±1%	21.45 W (0.72)	21.21 W	21.30 W	21.46 W	1.17	91
Difference (%)	1.03	0.52	1.04	0.61	N/A	N/A

***indicates the spectral filtering according to the IEC 62670-3, i.e. *SMR1* = 1±1% and *SMR2* = 1±3%.**

Table 6: P_{CSOC} estimations for all measurements from 25/06/2015 to 21/08/2015 in Albuquerque, NM using equations (5) to (11) along with the number of remaining datapoints after filtering of *SMR2* and Table 2. In parenthesis is the R^2 value of the regression. The percentage differences indicate the difference between maximum and minimum values.

Figure 3 shows a contour plot of *SMR1* against *SMR2* for *DNI* ≥ 750 W/m^2. The bold horizontal lines filter the *SMR1* = 1±1% and the vertical ones *SMR2* = 1±5%; these correspond to a *DNI* range between 850 W/m^2 to 900 W/m^2. Higher intensities occur during blue-rich skies, i.e. when the *AM* and/or the aerosol optical depth (*AOD*) are low and hence, higher *SMR1*. Having in mind the seasonal variations, the *SMR* distributions will vary, and therefore the CSOC estimations will be affected. Therefore, for an accurate CSOC evaluation, the rating has to be compared with data in different locations, at different times of the year in both hemispheres. Although a lower range of *SMR2* can avoid the seasonal or location dependencies, the "tighter" filtering can cause a significant reduction in the amount of data, introducing higher uncertainty in the CSOC estimation.

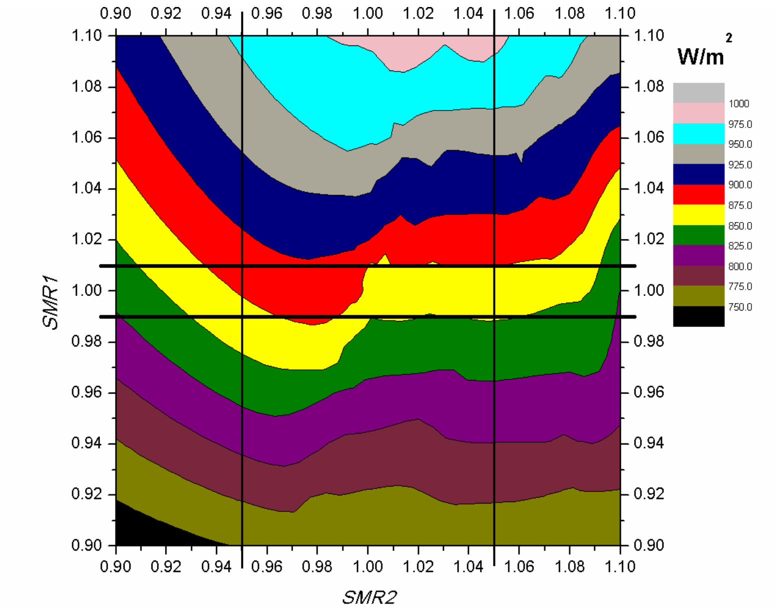

Figure 3: *SMR1* and *SMR2* contour plot for *DNI* ≥ 750 W/m² during the three selected days in Albuquerque, NM. The bold horizontal lines filter the *SMR1* = 1±1% and the vertical ones *SMR2* = 1±5%.

5. Power ratings determination of CPV monomodule using *SF* filter

In this section, the CSTC and CSOC power ratings are obtained following the same procedure described in IEC 62670-3 but using an alternative filtering criterion based on *SF* which is a spectral index that is also widely used in the PV community [23]. The *SF* is, basically, a normalisation of the I_{sc} where values above 1 indicate spectral gains, values below 1 indicate spectral losses and *SF* values equal to 1 indicate similar conditions to the reference spectrum (i.e. the ASTM G173-03 [3]) [24]. The advantage of this index is that it can be calculated without any special requirements, in terms of spectral monitoring using a spectroradiometer or component solar cells, given that the *DNI* and I_{sc} are measured. In addition, since the component solar cells are individual devices without concentrating optics, other effects that can occur within a MJ-based receiver, such as luminescent coupling [25], chromatic aberrations caused by the optics [26] or temperature dependent changes in the refractive index of the lens [27], are not captured. This spectral index however, accounts for these effects since it uses the measured I_{sc} of the CPV device [28].

5.1. CSTC power rating

The CSTC power rating was determined following the same outdoor translation procedure of the IEC 62670-3 (thoroughly described in Section 3 and applied in Section 4) using the *SF* as a filter for spectrum variations instead of the *SMR* indices. According to Part I, the majority of *SMR1* = 1±1%, correspond to a *SF* within 1±3%. Therefore, three filters were applied in this case, i.e. for *SF* = 1±1%, 1±2% and 1±3%.

From the three-day dataset, out of 1735 datapoints, the data were reduced to 1422, 693, 233 with "tighter" *SF* (i.e. 1±3%, 1±2%, 1±1% respectively), while with all measurements from 25/06/2015 to 21/08/2015, out of 14082 datapoints, the data were reduced to 10329, 7541, 3496 with "tighter" *SF*. This shows a significantly greater number of available datapoints for the power ratings estimations, compared to the *SMR* filters applied and analysed in Section 4. The results for the CSTC power rating estimations are given in Tables 7 and 8 for the three relatively clear-sky days and all measurements, respectively. The percentage differences of each estimation against the indoor CSTC power rating are also given. In the case of the three-day dataset, the P_{CSTC} varied between 25.28 W and 25.80 W, a difference of 2.04% which shows that the *SF* spectral filtering can have a relatively high effect on the power rating, compared to the *SMR* filters which may be attributed to the significantly larger amount of available datapoints. However, the tight spectral filter of *SF* = 1±1% exhibited a difference of 6.81%, compared to the indoor CSTC power rating; this shows that the *SF* filter demonstrated lower differences, compared to the lowest difference observed using the same three-day dataset filtered by *SMR* (by 1.41% absolute, see Table 3). When all measurements were taken into account however, the P_{CSTC} was found to be between 25.53 W and 25.82 W which is a 1.13% difference for the different ranges of *SF* filters. The percentage difference from the indoor CSTC power rating varied between 6.74% and 7.86%; this is a 0.35% absolute difference from the best performing CSTC method presented in Table 4, for all measurements. Similar to the

SMR filters applied in subsection 4.1, it can be observed that this procedure also underestimated the CSTC power rating obtained indoors.

***SF* Filter**	$\eta_{CSTC,avg}$ **(%)**	P_{CSTC} **(W)**	**No. of data**	**Difference from** $P_{CSTC,sim}$ **(%)**
SF = 1±3%	23.19	25.28	1422	8.85
SF = 1±2%	23.41	25.52	693	7.90
SF = 1±1%	23.67	25.80	233	6.81
Difference (%)	2.05	2.04	N/A	N/A

Table 7: P_{CSTC} **and** $\eta_{CSTC,avg}$ **estimations during the three selected days along with the number of remaining datapoints after filtering of *SF* and Table 2. The percentage difference indicates the difference between maximum and minimum values.** $P_{CSTC,sim}$ **refers to the indoor CSTC power rating obtained using a Helios 3198 solar simulator (i.e. 27.62 W, see Table 1).**

***SF* Filter**	$\eta_{CSTC,avg}$ **(%)**	P_{CSTC} **(W)**	**No. of data**	**Difference from** $P_{CSTC,sim}$ **(%)**
SF = 1±3%	23.43	25.53	10329	7.86
SF = 1±2%	23.54	25.66	7541	7.36
SF = 1±1%	23.68	25.82	3496	6.74
Difference (%)	1.06	1.13	N/A	N/A

Table 8: P_{CSTC} **and** $\eta_{CSTC,avg}$ **estimations for all measurements from 25/06/2015 to 21/08/2015 in Albuquerque, NM along with the number of remaining datapoints after filtering of *SF* and Table 2. The percentage difference indicates the difference between maximum and minimum values.** $P_{CSTC,sim}$ **refers to the indoor CSTC power rating obtained using a Helios 3198 solar simulator (i.e. 27.62 W, see Table 1).**

5.2. CSOC power rating

As in subsection 5.1, the CSOC power rating was determined using the *SF* filter as a criterion for spectrum variations. The results are given in Tables 9 and 10 for the three relatively clear-sky days and all measurements, respectively. The percentage differences from the CSOC power ratings determined following the complete procedure of IEC 62670-3 (resulting to $P_{CSOC,IEC62670}$ = 21.27 W and 21.40 W, see Tables 5 and 6 respectively) are also given. The CSOC power rating was found to be between 21.06 W and 21.53 W using the three-day dataset and between 21.24 W and 21.47 W using all measurements. The differences between the spectral filtering based on *SF* were found to be 2.21% and 1.08% which indicate a dependence on the filtering range. However, when the *SF* = 1±2% and 1±1% are compared, the differences fall to 1.26% and 0.60% in P_{CSOC}; it can therefore be concluded that the *SF* ranges lower than 1±3% should be applied, since the number of datapoints is still substantial (in this case up to 693 and 7541 depending on the dataset). The differences compared to the $P_{CSOC,IEC62670}$ were within 1.21% and 0.75% when the three-day dataset and all measurements are considered, respectively, with an almost perfect match found when the *SF* = 1±2% using the three-day dataset.

***SF* Filter**	**$\eta_{CSOC,avg}$ (%)**	**P_{CSOC} (W)**	**No. of data**	**Difference from $P_{CSOC,IEC62670}$ (%)**
SF = 1±3%	21.46	21.06	1422	0.99
SF = 1±2%	21.68	21.26	693	0.05
SF = 1±1%	21.94	21.53	233	1.21
Difference (%)	2.21	2.21	N/A	N/A

Table 9: P_{CSOC} and $\eta_{CSOC,avg}$ estimations during the three selected days along with the number of remaining datapoints after filtering of *SF* and Table 2. The percentage difference indicates the difference between maximum and minimum values. $P_{CSTC,sim}$ refers to the indoor CSTC power rating obtained using a Helios 3198 solar simulator. $P_{CSOC,IEC62670}$ refers to the CSOC power rating obtained following the procedure reported in IEC 62670-3 taking into account the measurements from the three selected days (i.e. 21.27 W, see Table 5).

***SF* Filter**	**$\eta_{CSOC,avg}$ (%)**	**P_{CSOC} (W)**	**No. of data**	**Difference from $P_{CSOC,IEC62670}$ (%)**
SF = 1±3%	21.65	21.24	10329	0.75
SF = 1±2%	21.75	21.34	7541	0.28
SF = 1±1%	21.88	21.47	3496	0.33
Difference (%)	1.06	1.08	N/A	N/A

Table 10: P_{CSOC} and $\eta_{CSOC,avg}$ estimations for all measurements from 25/06/2015 to 21/08/2015 in Albuquerque, NM along with the number of remaining datapoints after filtering of *SF* and Table 2. The percentage difference indicates the difference between maximum and minimum values. $P_{CSOC,IEC62670}$ refers to the CSOC power rating obtained following the procedure reported in IEC 62670-3 taking into account all measurements after filtering (i.e. 21.40 W, see Table 6).

6. Summary and conclusions

The power rating determination of PV is crucial for comparison purposes between technologies and also for the optimum selection of the type of technology used for a specific application, depending on the available solar resource, area, costs etc. In the case of CPV, the CSTC and CSOC power rating procedures are followed according to the recently published IEC 62670-3. Prior to this standard, other methods were used for the rating of this technology.

Bearing these in mind, this study evaluated the CSTC and CSOC power ratings of a CPV monomodule based on the newly developed IEC 62670-3. Due to the numerous suggestions within the IEC subgroup, regarding the limits of spectral filtering, different ranges of *SMR* were examined in order to investigate their sensitivity on the CSTC power determination. The results showed that the *SMR* range suggested by IEC 62670-3 is reasonable. However, when the outdoor P_{CSTC} was compared with the CSTC power rating obtained indoors, differences of up to 8.45% were found. The CSOC power rating was evaluated in terms of the spectral filtering but was also compared with the procedures described in ASTM E2527-09 and Steiner *et al.* Differences of up to 3.64% and 2.11% were observed depending on the number of data considered (i.e. the filters applied) and the method used. The extent of the differences in CSTC and CSOC were attributed to the Fresnel lens dependence on temperature amongst other effects that can occur within a MJ –based receiver (e.g. luminescent coupling) and also the tracker errors that occur when operated in the field.

Devices such as component solar cells are individually connected and do not employ any concentrating optics. Effects such as chromatic aberrations and luminescent coupling are not captured and therefore the *SMR* index becomes a device independent parameter that is useful for the evaluation of the spectral resource. For this reason, the IEC 62670-3 procedure was followed using an alternative device dependent parameter, the *SF*, as a spectral criterion instead of the *SMR* indices, in order to examine its applicability. The *SF* filtering criterion reduced the number of filtered data significantly which is a good indication of avoiding any bias on the power ratings estimations (up to 10329 available data compared to the 224 after filtering with the *SMR* indices). The difference of CSTC power rating against the one obtained indoors was reduced to 6.81% and 6.74% when *SF* = 1±1% compared to the 8.22% and 7.79% of the IEC 62670-3 (for *SMR2* = 1±3%). The CSOC power rating determination exhibited differences within 1.21% compared to the corresponding rating obtained using the IEC 62670-3.

Although the results of spectral filtering based on *SF* look promising, this index needs to be applied in different locations, during different times of the year and using different types of CPV modules. Upon successful validation of this method, using different modules in different locations, it may be more appropriate to use a calibrated reference monomodule with similar spectral characteristics with the CPV system under study, in order to obtain a more accurate power ratings outdoors. Moreover, it is worth investigating alternative procedures for the calculation of (a) cell temperature (e.g. as a function of module temperature instead of the electrical characteristics), (b) reference open-circuit voltage that needs to be determined indoors, (c) diode ideality factor that is assumed to be equal to 3 but is dependent on temperature and light intensity and finally, temperature coefficients of (d) open-circuit voltage and (e) efficiency; both are estimated based on the outdoor TTM. Most importantly, future work should focus on procedures that account for the optical efficiency variation due to temperature effects.

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Nomenclature

AM	air mass
AOD	aerosol optical depth
DNI	direct normal irradiance, W/m^2
GNI	global normal irradiance W/m^2
I	current, A
k_B	Boltzmann constant, eV/K
n	diode ideality factor
N_s	number of cells connected in series
P	power output, W
PW	precipitable water, cm
q	elementary charge, C
SF	spectral factor
SMR	spectral matching ratio
T	temperature, °C
V	voltage, V
WS	wind speed, m/s

Greek letters

β_{Voc}	temperature coefficient of V_{oc}
δ	temperature coefficient of η
η	efficiency

Subscripts

amb – ambient
avg - average
meas – measured
mod - module
mp – maximum power
oc – open-circuit
ref - reference
sc – short-circuit

sim - simulator

Abbreviations

ASTM - American Society for Testing and Materials
CEAEMA – Centre for Advanced Studies in Energy and Environment
CPV – Concentrating photovoltaic
CSTC - Concentrator Standard Test Conditions
CSOC - Concentrator Standard Operating Conditions
IEC – International Electrotechnical Commission
MJ - Multijunction
PV – Photovoltaic
TTM - Thermal Transient Measurements