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Rating of CPV Modules: Results of Module Round Robins

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Abstract. The results of three CPV module round robins are presented. Ten test labs around the world participated to the round robins in total. Each round robin used a different CPV module technology (Daido Steel, Soitec, Suncore). The data gathered at the test labs was used to test CSOC power rating procedures as basis for the IEC draft standard 62670-3. The deviation between the minimum and the maximum power output rated at the test labs was in average 4.4 % with a standard deviation of 1.8 $\%_{abs}$. This underlines that power ratings or CPV modules are reliable and reproducible.

INTRODUCTION

Three CPV module round robins have been realized between 2013 and 2015. Ten test labs around the world have been contributing. Each round robin used a different CPV module technology as specimen manufactured by Daido Steel, Soitec and Suncore, respectively. The aim of these three round robins was twofold. First, establishing standardized procedures to rate the power of CPV modules. These standardized procedures shall ensure comparable and reproducible test results between different test labs and different module technologies. Second, accuracy estimation for the power outputs rated at different labs and locations. The standardized power rating procedures for CPV modules are specified in the IEC draft standard 62670-3. CPV modules are rated at two sets of standard conditions defined in IEC 62670-1: concentrator standard operating conditions (CSOC) and concentrator standard test conditions (CSTC). CSOC correspond to a direct normal irradiance (DNI) of 900 W/m², an ambient temperature of 20 °C and a wind speed of 2 m/s, whereas CSTC are specified as a DNI of 1000 W/m² and a cell temperature of 25 °C. Both, CSTC and CSOC demand AM1.5d spectral conditions equivalent to conditions defined in IEC 60904-3. The current evaluation of the round robin activities aims for analyzing the CSOC rating procedures of CPV modules. In this work the results of the round robins are presented as a comparison of the rated power output at different test labs for different type of modules. Preliminary results of the SOPHIA round robin were already published in [1,2].

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THE SPECIMENS & PARTNERS

Within the three CPV module round robin activities different modules are used as test specimen and are measured at different participating test labs. Table 1 lists the main characteristics of each round robin and Table 2 the respective participants. In total ten labs participated the three round robins. The three different CPV module technologies from Daido Steel, Soitec and Suncore that were used are shown together in Figure 1 on a sun tracking unit at Fraunhofer ISE. All three module types use triple-junction lattice-matched solar cells. The module types differ in their geometrical concentration, lens type and secondary optical element (SOE). The Daido Steel [3] modules use PMMA Fresnel lenses, whereas the Suncore [4] and the Soitec [5] modules use silicone-on-glass (SoG) Fresnel lenses. Both, Daido Steel and Suncore modules use a SOE, whereas the Soitec modules do not. Each round robin uses one specific module type: The SOPHIA round robin was performed on four Soitec M400 modules, which were measured at seven partners around Europe. This round robin was part of the SOPHIA project funded by the EU. The Suncore round robin uses two Suncore DDM-1090X modules and five test labs in Europe and the USA were participating. In the NGCPV round robin four European labs performed power ratings on three Daido Steel 820-X modules. This round robin was part of the NGCPV project funded by the EU in Europe and NEDO in Japan.

TABLE 1. Main characteristics of the three round robins. SOE means secondary optical element and SoG means silicone-on-glass. The geometrical concentration (C_{geo}) is calculated as ratio of lens aperture area to cell designated area. 3JLM means lattice-matched triple-junction solar cell with the sub cell bandgaps of 1.9, 1.4 and 0.7 eV.

Round Robin	Nr. of modules	Nr. of partners	Module manufacturer	Module type	Cgeo	Cell type	Fresnel lens type	SOE	pyrheliometer, compoenent cells provided?	data evaluation done by
SOPHIA	4	7	Soitec	M400	500	3JLM	SoG	No	Yes	one partner
Suncore	2	5	Suncore	DDM-1090X	1090	3JLM	SoG	Yes	No	each partner himself
NGCPV	3	4	Daido	820-X	820	3JLM	PMMA	Yes	No	one partner

TABLE 2. Test labs participating in the three round robins listed in alphabetical order and with their country code.

SOPHIA	Suncore	NGCPV
CEA (FR)	CFV (US)	CEA (FR)
Enea (IT)	ISE (DE)	ENEA (IT)
Enel (IT)	NREL (US)	ISE (DE)
ISE (DE)	Sandia (US)	UPM (ES)
JRC (IT)	UPM (ES)	
RSE (IT)		
UPM (ES)		

In the SOPHIA and NGCPV round robin activities the calculation of the rated power outputs was performed by one of the participants for all partners applying the identical procedure, whereas in the Suncore round robin each participant used their in-house procedure to determine the power outputs rated at CSOC. For all three round robins the participating partners measured the I-V characteristics of the corresponding CPV modules outdoors on sun tracking units including the most important prevailing ambient conditions: direct normal irradiance (DNI), spectral matching ratio (SMR [6,7]]) and ambient temperature. The DNI is measured with a pyrheliometer and the SMR values via component cell sensors [6,8]. In the SOPHIA round robin a pyrheliometer and a component cell sensor was shipped together with the modules. In this manner each of the test labs used the same sensor for determining the DNI and the SMR values. In the Suncore and NGCPV round robin each partner used their in-house sensors. The three round robins were realized within a duration of about 2 years. Therefore, in the SOPHIA round robin each partner had around a 3.5 month time for installation, measurement and shipment. For this reason, not all partners were able to complete measurements at ambient conditions close to CSOC.

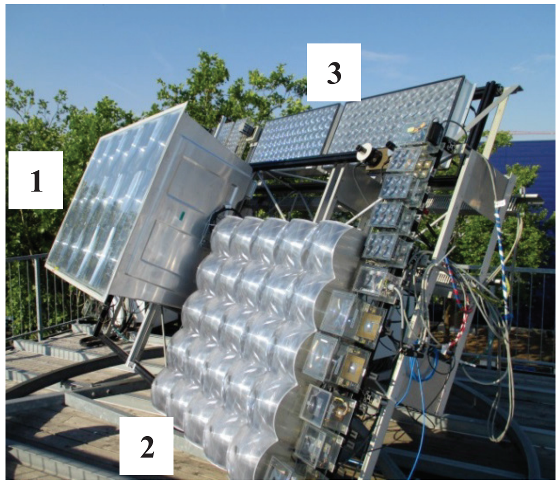

FIGURE 1. Module types used in the round robins on a sun tracking unit at Fraunhofer ISE: (1) Suncore DDM-1090X, (2) Daido Steel 820-X, (3) Soitec M400.

RATING PROCEDURES

The current IEC 62670-3 draft standard describes how to perform CPV module power ratings. IEC 62670-3 requires to measure outdoor I-V data of the CPV module to be rated on a sun tracking unit including the prevailing ambient conditions. Hereby, the most important ambient conditions are the direct normal irradiance DNI, the ambient temperature and the spectral distribution of the DNI. The spectral distribution is to be quantified using spectral matching ratios (SMR) [6,7]. SMR values are calculated from the readings of a lattice-matched triple-junction component cell sensor [6,8]. IEC 62670-3 defines three SMR values: SMR(1,2), SMR(1,3) and SMR(2,3), whereas '1' refers to the 1.9 eV, '2' to the 1.4 eV and '3' to the 0.7 eV component cell. In IEC 62670-3 a SMR filtering for all three SMR values of 1 ± 2.5 % is required. SMR values of 1 indicate relative spectral distributions close to AM1.5d ASTM G173-03 spectral conditions. After filtering for SMR values, the power output is normalized to 900 W/m² DNI and corrected to an ambient temperature of 20 °C in the case of CSOC rating. The final step is an averaging of the filtered, irradiance normalized and temperature corrected power output. The average value is then defined as the power output rated at CSOC. The rating procedures used in the three round robins differ from the current IEC 62670-3 rating procedure for two reasons. First, the current version of IEC 62670-3 was written considering the outcomes of the described round robins in this paper. Second, the round robins aimed for reasonable efforts and time schedules. The CSOC rating procedures used in the three round robins are as described in the following section.

The SOPHIA round robin was carried out during 2 years duration including the re-measurement of the modules by the first lab. Thus, only 3.5 months were available for shipment, preparation and measurement per partner. The SOPHIA round robin had the shortest test periods (one month) for each partner also including winter time. Therefore, not all labs were able to complete measurements at ambient conditions close to CSOC. As a consequence, in the SOPHIA round robin the I-V dataset was filtered for SMR(1,2) and SMR(2,3) within 1 ± 10 % instead of 1 ± 2.5 %. Furthermore, low ambient temperatures occurred during some test periods. However, low ambient temperatures have to be avoided for standardized rating procedures, especially when rating CPV modules with SoG lenses: The optical efficiency of SoG lenses has a non-negligible dependency on temperature [9]. Furthermore, no temperature filtering or corrections were applied to the I-V data. However, as requested in IEC 62670-3 the measured power output data remaining after filtering was scaled to a DNI of 900 W/m². The power output rated at CSOC was then calculated as an average value of the filtered and scaled power output data. Note that in the SOPHIA round robin every partner used the same pyrheliometer and component cell sensor shipped together with the modules to be measured. In this manner, measurement uncertainty resulting from the usage of different irradiance and spectral sensors could be excluded. All partners sent their measurement data to one partner, i.e Fraunhofer ISE, which also performed the data evaluation.

The power rating performed with the data gathered in the NGCPV round robin included a filtering for SMR(1,2) within 1 ± 2 %. No filtering for SMR(1,3), SMR(2,3), ambient temperature and DNI was applied. The power outputs remaining after SMR filtering were scaled to 900 W/m². No correction for ambient temperature was performed. The Daido Steel modules used in the NGCPV round robin apply PMMA Fresnel lenses. PMMA lenses have a much lower temperature dependency compared to SoG lenses [9]. Thus, the impact of ambient temperature on power output is much less pronounced. All partners sent their measurement data to one partner, i.e UPM IES, which performed the data evaluation. In the Suncore round robin each test lab used their in-house procedure and performed the data evaluation and power calculation themselves.

In the three round robins the number of days and data points left after filtering for ambient conditions is differing between the test labs. The minimum amount of data points left is five from one single day. The final IEC 62670-3 draft standard recommends data from at least three days.

RESULTS

The results of the three CPV module round robins are presented in the Tables shown in Figure 2 as a deviation of the rated power output of one specific partner from the mean power output of all partners.

(a) Suncore

CSOC	M1	M2
Lab 1	0.8%	3.0%
Lab 2	2.8%	-0.1%
Lab 3	?	?
Lab 4	-0.7%	-0.4%
Lab 5	-2.9%	-2.5%
Min-Max-Dev	**5.7%**	**5.5%**

(b) Daido Steel / NGCPV

CSOC	M1	M2	M3
Lab I	-1.7%	1.0%	2.0%
Lab II	0.9%	-1.1%	0.1%
Lab III	0.4%	-0.5%	-1.3%
Lab IV	0.4%	0.6%	-0.8%
Min-Max-Dev	**2.6%**	**2.1%**	**3.3%**

(c) Soitec / SOPHIA

Prev. Spec.	M1	M2	M3	M4
Lab A	-0.9%	3.5%	4.9%	3.3%
Lab B	-0.1%	3.6%	2.8%	1.7%
Lab C	-1.0%	-3.0%	-1.0%	-0.3%
Re First Lab	-0.9%	0.7%	0.9%	0.3%
Lab D	-	1.6%	3.6%	0.1%
Lab E	2.9%	4.4%	4.4%	3.5%
Lab F	-	10.8%	-3.6%	-8.7%
Lab G	-	-	-12.0%	-
Min-Max-Dev	**3.9%**	**7.4%**	**5.9%**	**3.8%**

FIGURE 2. The values in the table (a), (b) and (c) are deviations of the efficiency rated in the respective round robin to the mean value of all participating test labs. (a) Results of the Suncore round robin. The calculation of the efficiencies rated at CSOC was performed with the in-house procedure of each lab. The data of lab 3 is still under evaluation. (b) Results of the NGCPV round robin. The efficiencies are calculated by averaging all values left after filtering for SMR(1,3) within 0.98 – 1.02. (c) Results of the SOPHIA round robin rating at prevailing ambient conditions. The re-measurement at the first test lab 'Re First Lab' is included. The efficiencies are calculated by averaging all efficiencies left after removing measurements at extreme ambient conditions (filter: SMR(1,2) and SMR(2,3) within 0.9 – 1.1). The test periods for lab F and G were in the winter months with low ambient temperatures. The temperature dependence of the SoG Fresnel lenses caused the high deviation of efficiency from the mean value. For a rating of the modules low temperatures should be avoided. The min-max-deviations are calculated without the values of lab F and lab G. Modules without percentage value have not been measured at the respective test lab.

The results show a mean min-max-deviation of 4.4 % ± 1.8 $\%_{abs}$. for all modules and round robins. The min-max-deviation is the difference between the lowest and highest rated efficiency value of one module among the labs. This deviation is a measure for the reproducibility and comparability of the rated power outputs between the labs. Please note: This deviation is not corresponding to the measurement uncertainty for the absolute values of the rated power. The highest min-max-deviations were found for the SOPHIA round robin. The reason for this is the wider SMR filtering (1 ± 10 %) and the higher temperature dependency of the SoG lenses compared to the PMMA lenses used in the NGCPV round robin. Furthermore, the efficiency values of lab F and lab G were not used to calculate the mean min-max-deviation of 4.4 %. The test periods of lab F and lab G were in the winter time with low ambient temperatures which typically have to be avoided for reliable and comparable rating results. Thus, the results of those two labs are not representative. The lowest min-max-deviations were found in the NGCPV round robin. The min-max-deviations found there between 2.1 % and 3.3 % are extremely good results for a CPV module power rating. The findings of the three round robins are also used as a basis for the current IEC 62670-3 draft standard. The three round robins confirm that CPV power rating on the basis of filtering I-V dataset for ambient conditions close to the standard conditions and a calculation of the rated power using averaging of the remaining I-V data is suitable. CPV power ratings with low measurement uncertainty are feasible with this approach. Table 3 provides the main filtering criteria of the current IEC 62670-3 draft standard.

TABLE 3. I-V data requirement used for CSOC power rating following the current IEC draft standard 62670-3.

Parameter	Requirement
SMR(1,2)	0.975 – 1.025
SMR(1,3)	0.975 – 1.025
SMR(2,3)	0.975 – 1.025
DNI	700 – 1100 W/m²
$T_{Ambient}$	0 – 40 °C (manufacturers can demand a tighter filtering around 20 °C)
5 min avg. Wind speed	0.5 – 5 m/s
DNI/GNI	0.8 – 1.0
Tracker pointing error	-0.2 – +0.2°
DNI stability	40 min before I-V sweep: 40 % in max 10 min before I-V sweep: 10 % in max Directly before and after I-V sweep: 1 % in max

CONCLUSION

In this work the results of three round robins are presented. Ten test labs have contributed to the round robins. Three different module technologies have been characterized (Daido Steel, Soitec and Suncore). Therefore, the joint outcome of these round robins can be treated as significant and representative for CPV modules. One of the main findings is a mean min-max-deviation of 4.4 % ± 1.8 $\%_{abs}$. The min-max-deviation is calculated as the difference between the minimum and maximum rated efficiency measured at the test labs for one distinct module. The mean min-max-deviation of 4.4 % includes all modules and round robins. 1.8 $\%_{abs}$ is the standard deviation. 4.4 % describes the reproducibility of the rated power output between test labs and different test periods. This is a good result for CPV module technology as these were the first systematic round robin tests performed. The procedures used in the round robin were used as input for the IEC 62670-3 power rating draft standard. It can be assumed that 4.4 % is an upper limit for the reproducibility of the rated power when using IEC 62670-3 as the filtering criteria for ambient conditions are tighter and additionally a correction for temperature is requested in IEC 62670-3. The main outcome of the three round robins is that the power rating procedure and filtering criteria used in the current IEC draft standard 62670-3 are feasible for CPV power ratings with low measurement uncertainty.

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