SOPHIA CPV MODULE ROUND ROBIN: POWER RATING AT CSOC

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ABSTRACT: Within the European funded project SOPHIA, a Round Robin measurement on CPV module has been initiated. Seven different test laboratories located in Europe between 48 °N and 37 °N perform measurements of four SOITEC CPV modules. The modules are electrically characterized with different measurement equipment under various climatic conditions. One pyrheliometer and one spectral sensor based on component cells are shipped together with the modules. This ensures that the irradiance and spectrum, two factors with high impact on CPV module performance, are measured with the identical equipment at each site. The round robin activity is performed in close co-operation with the IEC TC82 WG7 power rating team in order to support the work on the CPV module power rating draft standard 62670-3. The resulting rated module power outputs at CSOC (Concentrator Standard Operating Conditions) are compared amongst the power rating methods and amongst the test labs. In this manner, a deviation in rated power output between different test labs and power rating methods is determined.

Keywords: CPV module, power rating, CSOC, round robin, performance testing, standardization

1 INTRODUCTION

The International Electrotechnical Commission Technical Committee 82 working group 7 (IEC TC82 WG7) is working on developing several standards relevant for Concentrator Photovoltaics (CPV). Two of these standards will be applied and evaluated through this work. These two standards are IEC 62670-1, “Concentrator Photovoltaic (CPV) Performance Testing - Standard Conditions”[1] and IEC 62670-3, “Concentrator Photovoltaic (CPV) Performance Testing - Performance Measurements and Power Rating” [2]. IEC 62670-1 defines the standard conditions for the performance testing. Thereby, two standard conditions are distinguished: Concentrator Standard Test Conditions (CSTC) and Concentrator Standard Operating Conditions (CSOC). CSTC are at a direct normal irradiance (DNI) of 1000 W/m² and with a cell temperature of 25 °C. CSOC are at a DNI of 900 W/m², at an ambient temperature of 20 °C and at a wind speed of 2 m/s. Both, CSTC and CSOC are demanding for AM1.5 direct spectral conditions, which are described in IEC 60904-3 [3]. The standard conditions are already fixed within the IEC standard, whereas the performance measurement and power rating procedures are still under discussion by the power rating subgroup of IEC TC82 WG7. The CPV module round robin presented in this paper aims for investigating different power rating procedures to support the finalization of a power rating standard.

2 SPECIMEN & PARTNERS

As test specimens four SOITEC CX M400 CPV modules [4] and one ISE-SOITEC mono-module are used. The full size CPV modules were provided free of charge by SOITEC and were taken randomly from production. The CX M400 modules have an area of 0.32 m² and consist of 98 lattice-matched triple-junction solar cells and Silicone-on-Glass (SoG) Fresnel lenses [4].

The ISE-SOITEC mono-module is manufactured using the same lens and solar cell assembly technology as the full size modules. In contrast to the full size CPV modules, the mono-module has been equipped with two PT100 temperature sensors. In this manner, the lens plate and heat sink temperature can be measured. As the SOITEC modules use Silicone-on-Glass (SoG) lenses, the temperature of the Fresnel lenses [5] might have a significant impact on the power rating of the modules. The measured lens plate temperature will enable detailed analysis of such effects and it is expected that the data gathered will help in proposing procedures to IEC TC82 WG7 on how to account for the temperature of the optics in the power rating of CPV modules.

The shipment of the CPV modules includes a Kipp & Zonen pyrheliometer for the measurement of DNI and a component-cells based spectral sensor [6]. The spectral sensor quantifies the spectral distribution of the DNI. In this manner, the laboratories can compare the measured respective data with data measured by their in-house equipment. In addition, it assures that two factors with high influence on performance - irradiance and spectrum - are measured with identical equipment at each site. In this way the round robin focuses on the comparison of the specific rating procedures and minimizes the uncertainties associated with the measurement equipment. Less critical equipment, used to measure meteorological data like ambient temperature, wind speed and global irradiance, is provided by each partner.

All partners of the round robin agreed on using the same measurement guidelines. This included mounting and alignment procedures but also requirements for the duration of data collection. The requirements and the alignment procedure are published together with first results in [7].

Measurements for the SOPHIA CPV module round robin started in June 2013 and measurements at the 5th partner's location have been finished up to now. The round robin activity will be finalized in October 2014.

The seven partners, located in Spain, France, Germany and Italy, are listed in Table I together with altitude and location.

Table I. Partners (in alphabetic order) participating in the SOPHIA CPV module round robin together with their geographic location.

Partner	Location	Altitude
CEA-INES	Le Bourget du Lac, France 45.65N, 5.87E	230 m
ENEA	Portici, Italy 40.81N, 14.34E	0 m
Enel I&R	Catania, Italy 37.40N, 15.00E	30 m
Fraunhofer ISE	Freiburg, Germany, 48.01N, 7.83E	270 m
IES-UPM	Madrid, Spain 40.45N, 3.71W	695 m
JRC	Ispra, Italy 45.82N, 8.63E	220 m
RSE	Piacenza, Italy 45.05N, 9.70E	61 m

Figure 1: Modules and equipment of the SOPHIA module round robin mounted on the sun tracking unit at Fraunhofer ISE in Freiburg: (1) SOITEC MX400 modules (2) SOITEC-ISE mono-module (3) pyrheliometer (4) component cell sensor

3 POWER RATING METHODS

Measurement data of three partners are already evaluated. In this paper the measurement data gathered at these three locations is used to evaluate various power rating methods at CSOC. In this manner, a deviation in rated power output between these different test laboratories and power rating methods is determined.

Most of the power rating methods demand for filtering of the measurement data before applying the method. We perform the data filtering in three steps: (i) Remove physical unreasonable data: short-circuit current I_{SC}, open-circuit voltage V_{OC}, fill factor, efficiency and DNI have to be greater than zero. Fill factor, efficiency have to be below 100 %. The ratios of current at maximum power to I_{SC} and voltage at maximum power to V_{OC} have to be between 0 and 1. (ii) Remove unstable conditions: module must be on sun for at least 30 min before each IV curve measurement: DNI must not vary before IV sweeps by more than 50 % within 30 min, by 10 % within 10 min and by more than 1 % before and after the IV sweep. This shall assure stable cell and lens temperatures. (iii) Filtering for DNI, ambient temperature, wind speed, tracking accuracy and spectral conditions to have datasets not too far of CSOC: 700 W/m² < DNI < 1100 W/m², 0 °C < ambient temperature < 40 °C, 0 m/s < wind speed < 6 m/s, tracking accuracy < 0.2 °. The filtering for spectral conditions is performed using the spectral matching ratios SMR defined in equation 1 [8]. The short-circuit currents I_{SC} are measured by component cells of a lattice-matched triple-junction solar cell. The equation 1 shows exemplarily the calculation of an SMR value using the top (t) and the middle (m) sub cell. A SMR value of one indicates AM1.5d similar spectral conditions. Two SMR values are calculated in this work: SMR_1 between top and middle cell, SMR_2 between top and bottom cell.

$$SMR(t,m) = \frac{I_{SC}(t, measured)/I_{SC}(t, AM1.5d)}{I_{SC}(m, measured)/I_{SC}(m, AM1.5d)} \qquad 1$$

In general, there are three different methods to perform a power rating: regression, averaging and translation.

The averaging method filters the gathered measurement data very tightly around the desired ambient conditions and calculates a mean value using the remaining data.

The translation method translates each individual measurement data from the measurement conditions to the desired conditions by suitable equations. A mean power is calculated from the translated values.

The regression method describes the dependency of power output on ambient conditions by empirical functions. These functions are fitted to measurement data to extract fit parameters. The functions together with the fit parameters allow the calculation of the power at the desired ambient conditions.

The averaging method used in this work is performed by tight filtering for spectral conditions and calculating a mean power output value as described by equation 2.The measured power outputs P_i at the prevailing direct normal irradiance DNI_i are linearly scaled to 900 W/m². N is the total number of measured power left after filtering. The DNI is only limited to 700 up to 1100 W/m².

The translation method we exemplarily use in this paper is represented by equation 3. This equation is similar to equation 2. The difference between the two equations is the correction of the measured DNI using the SMR_2 value. This correction takes into account, that sun light is absorbed by water vapor in the IR wavelength regime, which is considered by the pyrheliometer. This absorption reduces the measured DNI, but does not affect the power output of the lattice-matched triple-junction solar cell. The Germanium sub-cell of the lattice-matched triple-junction solar cell does convert sun light in the IR region to electrical current. But this electrical current does only contribute marginally to the power output of the triple-junction solar cell due to the high excess current of the Germanium cell and due to the series connection of the three sub cells.

The third rating method in this work is a multi linear regression method using the formulas published in [9]. The formulas describe the module power output as a function of DNI, ambient temperature and spectral parameter Z [9].The spectral parameter Z quantifies the prevailing spectral conditions by the usage of component cell sensors [6, 10]. The spectral parameter Z is depending on SMR as shown in equation 5. The advantage of Z is its symmetry. Z(top,mid) equals -Z(mid,top), whereas no such symmetry for SMR(top,mid) and SMR(mid, top) is possible.

The filtering for spectral conditions using the SMR values is different for each of the three power rating methods. The averaging method needs tight filtering of SMR_1 and SMR_2, whereas the regression method does not filter for SMR values. A tight filtering for SMR_1 and a broad filtering for SMR_2 is done for the translation method. The explicit SMR filters are given in the next section.

$$P_{CSOC} = \left(\sum_i P_i \cdot \frac{900}{DNI_i} \right) \Big/ N \qquad 2$$

$$P_{CSOC} = \left(\sum_i P_i \cdot \frac{900}{DNI_i \cdot SMR_{2,i}} \right) \Big/ N \qquad 3$$

$$P_{CSOC} = P(SMR_1, DNI, T_{Ambient}, k_1, \ldots, k_j) \qquad 4$$

$$Z = 1 - \frac{2}{1 + SMR} \qquad 5$$

4 RESULTS AND DISCUSSION

In Figure 2 the averaging method is compared to the regression method. The maximum deviation in module power output shown in Figure 2 is the relative difference in the maximum rated power output to the minimum rated power output among the rated power outputs of the three test labs. For the averaging method the SMR_1 value has to be within ± 1 % and the SMR_2 within ±10% around 1. For the regression method the SMR values are not limited. Figure 2 shows that the maximum deviation is below about four per cent for all four modules and both methods. If we neglect module A, the averaging method shows lower maximum deviations below about two per cent compared to the regression method. The question is why the maximum deviation of module A is double compared to the other three modules. One reason could be the different ambient conditions of the measurement period of that module at one test lab. At one test lab three modules were measured at once, while module A has been measured in a period after these modules.

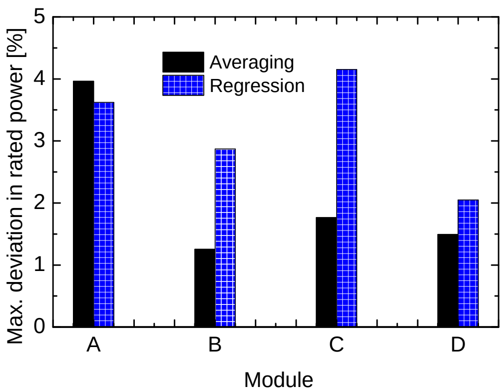

Figure 2: Maximum deviation of rated module power output between three test labs. The graph shows a comparison between the averaging and the regression method.

Figure 3 shows the DNI, Figure 4 the ambient temperature and Figure 5 the SMR_2 as mean values and standard deviation after filtering for SMR_1 and SMR_2 for each test lab and each module for the averaging method.

The measurement period of Test lab 1 has the highest mean DNI and the lowest mean ambient temperature, whereas the period of test lab 3 has the lowest DNI and the highest ambient temperature. The mean values shown in Figure 5 of mean SMR_2 are all above one for all three test labs. The largest difference in SMR_2 between the three labs is about 0.05 for module A. For this reason, a tighter filtering for SMR_2 seems to be necessary to get more comparable spectral conditions between the three test periods. Note, that the number of measurement data at CSOC in the test period of the three partners is different. The modules in the test periods of partner 1 and partner 2 were measured on 5 clear sky days and in the test period of partner 3 the module were measured for 3 clear sky days. Table II shows the number of measurement data left after filtering and used to apply the power rating methods.

Table II. Number of measurement data left after filtering for the filter criteria of the power rating method. The numbers are separated by module and partner (P1, P2, P3)

Module	P1	P2	P3	Method
A	70	13	72	Averaging & translation
B	87	13	68	
C	110	18	66	
D	62	10	67	
A	31	6	21	Averaging with tight SMR_2 filter
B	72	5	20	
C	80	6	20	
D	45	6	21	
A	479	373	930	Regression
B	623	336	972	
C	641	382	983	
D	423	336	977	

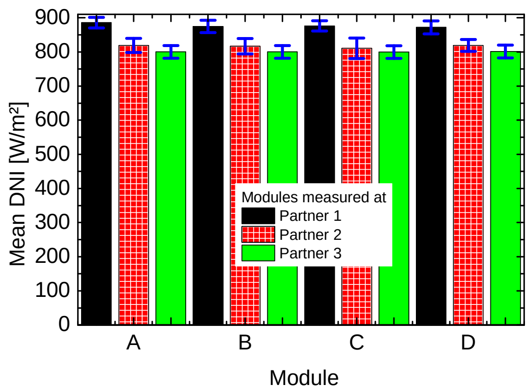

Figure 3: Mean measured DNI and standard deviation for each test lab and CPV module. Only DNI left after applying all filters for the averaging method are considered.

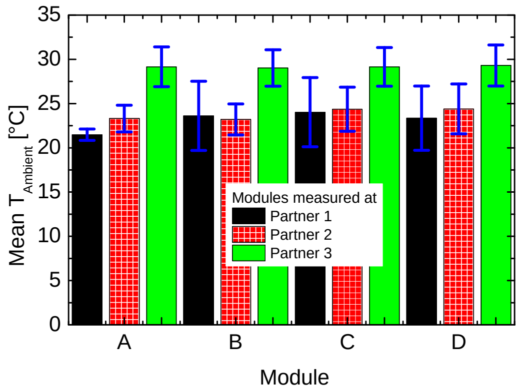

Figure 4: Mean measured ambient temperature $T_{Ambient}$ and standard deviation for each test lab and CPV module. Only ambient temperature left after applying all filters for the averaging method are considered.

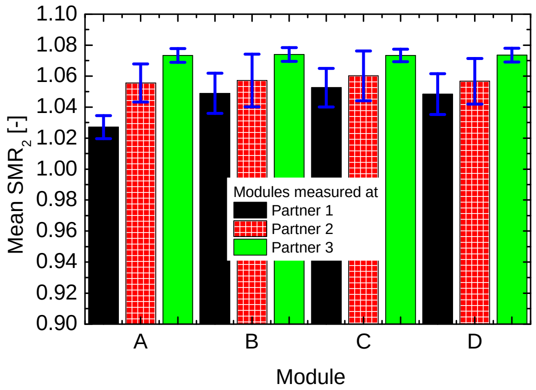

Figure 5: Mean measured SMR_2 and standard deviation for each test lab and CPV module. Only SMR_2 which were left after applying all filters for the averaging method with broad SMR_2 filter condition are considered.

The prevailing different spectral conditions during the test periods at the test labs make a further limit of SMR_2 beyond 1.0 ± 0.1 impossible, while SMR_1 is limited to 1.0 ± 0.01. Only few datasets would be left after a more rigorous SMR_2 filtering. A stricter limit for SMR_2 is only possible if the filter for SMR_1 is reduced to the range of 0.96 ± 0.01. Then, SMR_2 can be limited to the range of $1.05 \pm 0.0.05$. Figure 6 shows the mean values and standard deviation after applying these SMR criteria. The mean values of SMR_2 are overall closer to 1 compared to Figure 5. And the maximum difference in SMR_2 between the labs 1 and 3 for module A is lowered to 0.02. But, now for lab 2 the difference in mean SMR_2 is about 0.04.

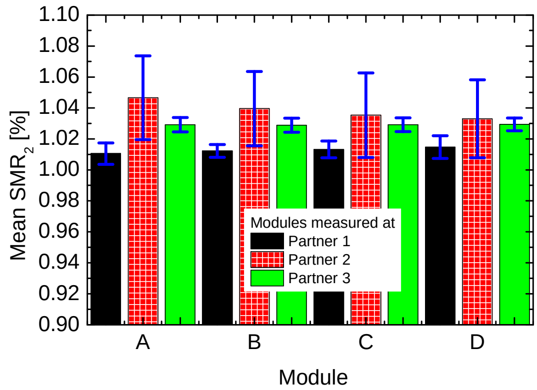

Figure 6: Mean measured SMR_2 and standard deviation for each test lab and CPV module. Only SMR_2 which were left after applying all filters for the averaging method with tight SMR_2 filter conditions are considered.

Figure 7 shows the maximum deviation between the three test labs for four modules in comparison of the three power rating methods. For the averaging method the broad SMR_2 filter is compared with the tight SMR_2 filter. The tight SMR_2 filter reduced the maximum deviation for module A and B, whereas the maximum deviation for module C and D is slightly increased. The prevailing spectral condition in the test periods of the three test labs does not allow for an even tighter filter of SMR_2. Therefore, it cannot be clarified within this work if a tighter filter of SMR_2 would further reduce the deviation for module A for the averaging method.

The maximum deviation of the SMR_2 translation method shown in Figure 7 is below 2.5 % for all four modules. This means that the SMR_2 translation method shows the lowest maximum deviation of the three methods.

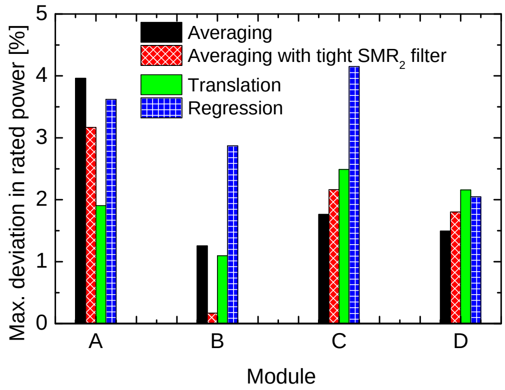

Figure 7: Maximum deviation of the rated power output between the three test labs. The graph shows a comparison of the averaging, translation and regression rating method. For the averaging method a broad and a tight filter for SMR_2 are shown.

5 CONCLUSION

A module round robin with seven partners at different locations has been started under the framework of the European project SOPHIA. The modules have been already measured by five partners and are at the moment of the writing on the way to the sixth partner. The data of the first three partners have been initially used to compare different power rating methods at CSOC conditions. The three methods cover averaging, regression and translation methods. The translation method uses the SMR_2 value for a first order correction of the measured DNI in respect to water vapor absorption in the IR wavelength region. This translation method shows the lowest maximum deviation in rated power output between the three test labs of below about 2.5 %. The second lowest maximum deviation shows the averaging method with below about 3 %. The prevailing spectral conditions on the test period does not allow for tighter filter for SMR_2, which could have reduced the maximum deviation of the averaging method. However, the maximum deviation of the rated power output could be lowered by considering the SMR_2 value additionally to the SMR_1 value in the translation and in the averaging method. This demonstrates that even for CPV modules using lattice-matched triple-junction solar cells with high excess currents in the Germanium bottom cell, the consideration of the output of the Germanium component cell sensor is mandatory.

The third lowest maximum deviation is found for the used regression method with below about 4 %. Please, note that a maximum deviation of about 4 % is already a good result for a CPV power rating method. All proposed power rating method make further analysis and testing at the other four locations of the round robin necessary.

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