Uncertainty Estimation of Spectral Matching Ratio Based Power Rating of CPV Modules

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Abstract. The concentrator standard conditions are defined in the standard IEC 62670-1. Those conditions demand for spectral conditions equivalent to AM1.5d as described in IEC 60904-3. The power output of CPV modules has to be rated at the concentrator standard conditions and thus at AM1.5d spectral irradiance. According to IEC standard 62670-3 the prevailing spectral conditions have to be characterized using spectral matching ratios (SMR). The SMR values have to be within three percent of unity to allow for standardized power ratings. The SMR values are calculated from component cell sensor readings. The most commonly used component cells are based on lattice-matched triple-junction cell structures with bandgaps of 1.9, 1.4 and 0.7 eV. In this work, the usage of these component cells for power ratings on CPV modules equipped with other types of multi-junction cells is investigated. This investigation is based on representative power outputs of CPV modules. These power outputs were calculated using i) the spectral irradiance modeling software SMARTS2, ii) measured external quantum efficiencies and iii) the two-diode model. The outcome of this investigation is an estimation for the measurement uncertainty of rated CPV module power output when using the SMR filtering approach recommended in IEC 62670-3.

INTRODUCTION

According to the IEC standard 62670-1 the output power of CPV modules has to be rated at concentrator standard conditions. The concentrator standard conditions demand for spectral conditions equivalent to AM1.5d as described in IEC 60904-3. In reality this spectral irradiance is rarely available. Therefore, how to deal with the prevailing spectral conditions available during the CPV module power rating procedure, is described in the IEC standard 62670-3. The approach is based on spectral matching ratios (SMRs) determined using component cell sensors [1,2,3]. Component cells have the same optical characteristics as the sub cells of the equivalent multi-junction cell but show the electrical characteristic of the single sub cell. Today's commonly used component cells are linked to lattice-matched triple-junction cell structures with bandgaps of 1.9, 1.4 and 0.7 eV. Using these component cells, the integral value of the effective spectral irradiance in distinct wavelength regions is determined. The SMR values are calculated as the ratio of two normalized component cell currents. The normalized component cell current is the ratio of the component cell output current under the prevailing spectral conditions divided by the respective component cell output current under AM1.5d reference conditions. SMRs close to unity indicate spectral conditions close to reference conditions. In the IEC 62670-3 rating procedure the SMR values are demanded to be around unity and thus they are used as filter to restrict the module power output data in respect to the prevailing spectral conditions. In this work an uncertainty estimation of this method is performed. Therefore an appropriate model to calculate the CPV module power output has been established. This model is using the software SMARTS2 to calculate spectral irradiances and combines these with measured external quantum efficiency data of different types of multi-junction cells and the two-diode model to calculate the current-voltage characteristic and hence a power output representative for CPV modules. The outcome of this investigation is threefold: i) lattice-matched triple-junction solar cells are suitable for SMR based power ratings. ii) component cells used for SMR value determination don't need to match the cells used in the device under test and iii) the power rating based on SMR values can be performed with low measurement uncertainty.

SPECTRAL MATCHING RATIO

Spectral matching ratios (SMR) are commonly derived from component cell sensor readings [1,2,3]. The component cells used in those sensors have the same optical characteristic as the equivalent multi-junction solar cell but the electrical characteristic of one single sub cell only. SMR values are calculated from the component cell current densities J_{SC} measured under prevailing spectral condition and measured under AM1.5d reference spectral conditions J_{SC}(AM1.5d). SMR values are calculated according to IEC 62670-3 as follows:

$$SMR(i,j)=(J_{SC},i/J_{SC},i(AM1.5d)) \;/\; (J_{SC},j/J_{SC},j(AM1.5d))$$

Whereas the indexes i and j assign distinct component cells of distinct sub cells in a multi-junction solar cell. In this manner, for a multi-junction solar cell with n sub cells n^2 SMR values can be calculated. SMR values where i and j assign the same sub cells and SMR values where sub cell i has a lower band gap energy as sub cell j are not used. For component cell sensors based on triple-junction solar cells three SMR values are calculated: SMR(1,2), SMR(1,3) and SMR(2,3). The numbers are assigned to the component cells in the ordering of their band gap energies, where the component cell 1 has the highest band gap energy. According to IEC 62670-3 a prevailing spectral condition can be treated as close to AM1.5d reference conditions when all these three SMR values are within 3 % of unity.

MODELING APPROACH

The investigations performed in this work are based on a common modeling approach [4,5]. The modeling approach consists of three main elements: solar spectral irradiance modeling software SMARTS2 [6,7], measured external quantum efficiencies (EQE) and the two-diode model of multi-junction solar cells.

The software SMARTS2 is used to calculate spectral irradiances. The most important input parameters for the investigations in this work are air mass (AM), aerosol optical depth (AOD) and precipitable water (PW). The resulting spectral irradiances are multiplied with a concentration factor to consider the increased irradiance in CPV modules. In this work, a concentration factor of 500 is used. The EQEs of the investigated multi-junction solar cells are measured using a grating monochromator set up [8]. Figure 1 shows the EQE of the investigated cell types. In particular Figure 1 shows the EQE of a lattice-matched triple-junction solar cell [9], an inverted metamorphic triple-junction solar cell [10,11], an upright metamorphic triple-junction solar cell [12] and a wafer-bonded four-junction solar cell [13,14]. The sub cell EQE data of all cell types shown in Figure 1 is scaled in a manner that for each cell type the sub cell with highest absolute EQE is normalized to 100 %. The same normalization factor is applied to the other sub cells, so that the relative difference between the sub cells is unchanged.

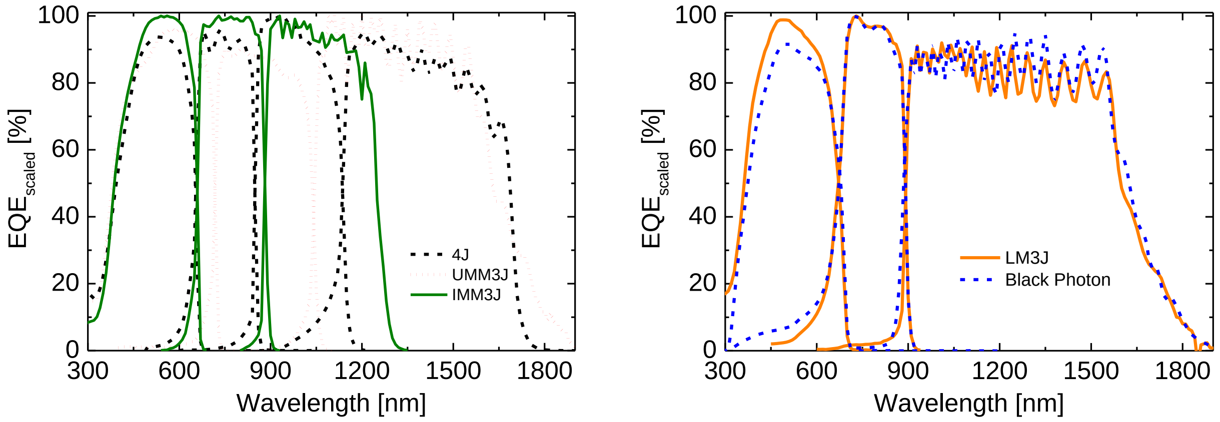

FIGURE 1. External quantum efficiencies measured with a grating monochromator set up [8]. (Left) EQE of an inverted metamorphic triple-junction (3JIMM) [10,11], an upright metamorphic triple-junction (3JUMM) [12] and a wafer bonded four-junction cell (4J) [13,14]. (Right) EQE of commercially available component cell sensor [15] and of a lattice-matched triple-junction cell (3JLM) [9]. The EQE data of all cell types is scaled in a manner that for each cell type the sub cell with highest absolute EQE is normalized to 100 %. The same normalization factor is applied to the other sub cells.

The two-diode model is used to calculate the current-voltage characteristic representative for CPV modules using a distinct multi-junction cell type. The maximum power output and efficiency value is derived from this current-voltage characteristic. The input parameters of the two-diode model are for each sub cell dark saturation currents J_{01}, J_{02} and the current density J_{SC}. The J_{SC} values are calculated from the spectral irradiance and the measured EQE. The impact of the optics is not taken into account. The J_{01} and J_{02} are calculated as described in [16] taking into account the band gap energies and the radiative recombination only. The series and parallel resistances are neglected in this work.

In this manner, efficiency values of CPV modules using different types of multi-junction solar cells under distinct spectral conditions are calculated.

Furthermore, the J_{SC} derived from the cell EQE of one commercially available component cell sensor based on lattice-matched triple-junction solar cells are used for SMR value calculation.

REPRESENTATIVE DATASET OF SPECTRAL CONDITIONS

The basis of the investigation performed in this work is a representative dataset of spectral conditions. These spectral conditions are calculated using the software SMARTS2 [6,7]. The input parameters for SMARTS2 define the calculated spectral irradiance. The input parameters with the highest impact on the spectral irradiance are air mass (AM), aerosol optical depth (AOD) and precipitable water (PW). All other parameters are set to the value defined for the AM1.5d reference spectral irradiance as described in IEC 60904-3. The values for AM, AOD and PW are varied independently of each other over wide ranges in order to cover all spectral conditions which could occur during a CPV module power rating. AM is varied between 1 and 12, PW between 0 and 12 and AOD between 0 and 1. 740.000 spectral irradiances have been calculated in this manner. IEC 62670-3 request direct normal irradiances between 700 and 1100 W/m². 125.000 spectral irradiances are within this range, all others have been discarded. Figure 2 and Figure 3 shows the used input values of AM, AOD and PW as histogram plots. Figure 3 additionally shows the distribution of the resulting DNI values for the 125.000 spectral irradiances. Furthermore, the input parameters and DNI values remaining after filtering for SMR values within 3 % of unity are marked in Figure 2 and Figure 3. The number of spectral irradiances left after this SMR filtering is 3600. For each of the 125.000 spectral irradiances efficiency values representative for CPV modules are calculated as described in the previous section.

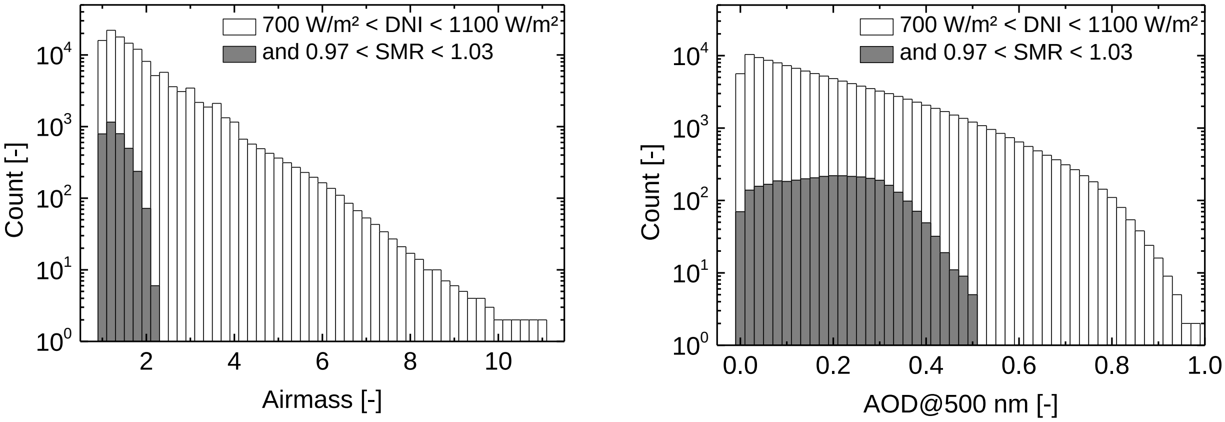

FIGURE 2. Input parameters air mass (AM, left) and aerosol optical depth (AOD, right) as histogram plots. The input parameters are shown for spectral irradiances with a direct normal irradiance (DNI) between 700 and 1100 W/m², as well as when additionally filtered for SMR values within 3 % of unity.

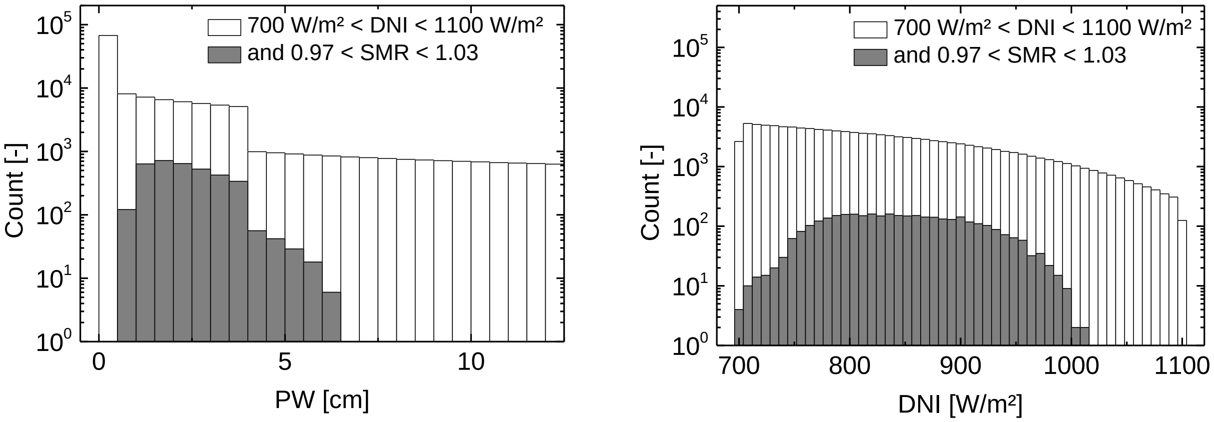

FIGURE 3. (left) Input parameter precipitable water (PW) as histogram plot. The input parameter is shown for spectral irradiances with a direct normal irradiance (DNI) between 700 and 1100 W/m², as well as when additionally filtered for SMR values within 3 % of unity. (right) Distribution of DNI of the spectral irradiances calculated with SMARTS2 using the AM, AOD and PW values as input parameters.

RESULTS

Figure 4 shows the histogram of normalized efficiency values of CPV modules using lattice-matched triple-junction and four- junction solar cells, respectively. These efficiency values are normalized to the efficiency calculated for AM1.5d reference spectral irradiance. It has to be noted that only efficiency values for spectral irradiances with a DNI between 700 and 1100 W/m² are calculated. Efficiency values calculated for spectral irradiances with SMR values within 3 % of unity are marked in Figure 4. The SMR values are calculated using the EQE of a commercially available component cell sensor [15], which is based on lattice-matched triple-junction solar cell technology.

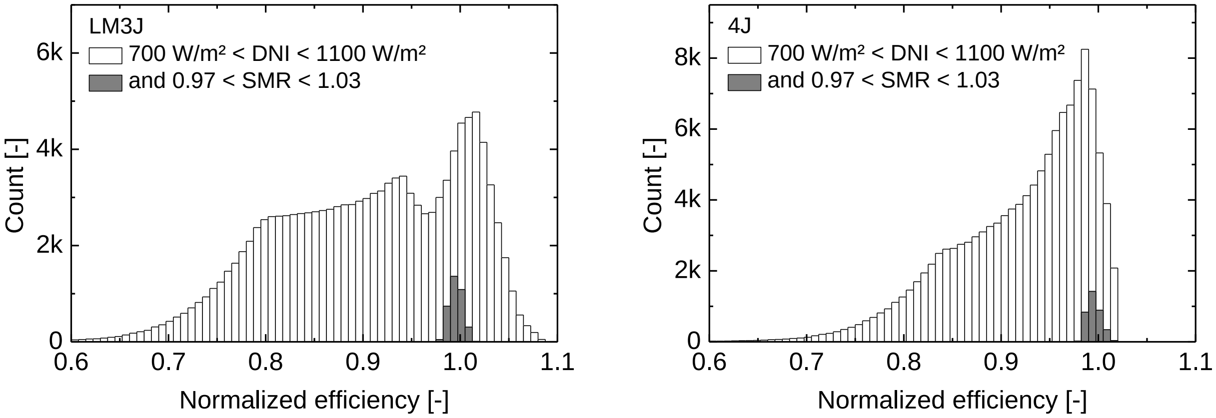

FIGURE 4. Histogram of normalized efficiency values representative for CPV modules using lattice-matched triple-junction (left) and four-junction solar cells (right). The efficiency values are normalized to the efficiency calculated at AM1.5d reference spectral conditions. The histograms show efficiency values calculated for spectral irradiances with a DNI within 700 and 1100 W/m². Furthermore, the efficiency values for spectral irradiances with all SMR values within 3 % of unity are marked. The histogram of efficiency values calculated for the UMM3J and IMM3J cells are similar.

Table 1 shows the statistics of the calculated efficiency values left after filtering for SMR values within 3 % around unity based on a lattice matched component cell sensor. The results for all four investigated cell types are shown. As in Figure 4 the efficiency values are normalized to the efficiency value calculated for AM1.5d spectral irradiance. For each cell type Table 1 lists the mean efficiency, the min-max-deviation and the lower and upper efficiency limit. The mean efficiency is the arithmetic mean of the efficiency values left after SMR filtering. The lower efficiency is the lowest and upper the highest efficiency value for spectral irradiances with SMR values within 3 % of unity. The min-max-deviation is the difference between upper and lower efficiency limit. The mean efficiency values are all within 0.6 % of the AM1.5d efficiency value. The reason for this small deviation is the huge variety of spectral irradiances used in this work. Such a huge variety can rarely be found in the real word. Therefore, the mean value is most likely not a representative measure for the measurement uncertainty introduced by the SMR filtering approach recommended in IEC 62670-3. Test labs could perform the rating procedure in a test period with spectral irradiances close to the SMR filtering boundaries only. This worst case scenario is covered by the upper and lower efficiency limit listed in Table 1. These two efficiency limits are between - 2.4 $\%_{\text{rel.}}$ and + 1.7 $\%_{\text{rel.}}$ for all four cell types. These values are representative for the measurement uncertainty introduced by the SMR filtering approach used for the power rating procedure for CPV modules. The difference between these two limits is called min-max-deviation in Table 1. This min-max-deviation quantifies the deviation in rated module power output occurring in worst case between different test labs and/or test periods. The highest min-max-deviation found for the four investigated cell types is 3.9 %. The calculation of efficiency limits and min-max-deviation corresponding to the uncertainties expected in the power rating of CPV modules originating from the spectral filtering based on SMR values shows reasonable values. Therefore, a power rating approach using lattice-matched triple-junction cell based SMR values filtered for ± 3 % around unity seems appropriate.

TABLE 1. Statistics of the efficiency values left after filtering for SMR values within 3 % of unity for the four investigated multi-junction cell types. The statistics show the mean efficiency and the upper and lower efficiency limits. The min-max-deviation is the difference between upper and lower efficiency limit. The efficiency limits are a measure for the measurement uncertainty and the min-max-deviation a measure for the deviations which can occur for power ratings performed at different test labs and/or test periods. The SMR values used for filtering are calculated using lattice-matched triple-junction cells as basis for the component cells. The efficiency values are normalized to the efficiency calculated for AM1.5d spectral conditions.

Cell type	Mean efficiency	Lower efficiency limit	Upper efficiency limit	Min-max-deviation
LM3J	0.996	- 2.3 $\%_{\text{rel.}}$	+ 1.5 $\%_{\text{rel.}}$	3.8 $\%_{\text{rel.}}$
IMM3J	0.994	- 2.4 $\%_{\text{rel.}}$	+ 1.5 $\%_{\text{rel.}}$	3.9 $\%_{\text{rel.}}$
UMM3J	0.996	- 1.8 $\%_{\text{rel.}}$	+ 1.7 $\%_{\text{rel.}}$	3.5 $\%_{\text{rel.}}$
4J	0.995	- 2.0 $\%_{\text{rel.}}$	+ 1.7 $\%_{\text{rel.}}$	3.7 $\%_{\text{rel.}}$

CONCLUSION

In this work the standardized rating of the CPV module power output is investigated. In particular the measurement uncertainty introduced by the spectral filtering is studied. According to IEC 62670-1 the power output of CPV modules has to be rated under AM1.5d reference spectral conditions. The power rating procedure described in IEC 62670-3 recommends the usage of spectral matching ratios calculated from component cell readings to assure that the prevailing spectral irradiances are close to AM1.5d reference conditions. IEC 62670-3 defines spectral irradiances as being close to AM1.5d when all SMR values are within 3 % of unity. Furthermore, IEC 62670-3 recommends using component cells with the band gap energies of 1.9, 1.4, and 0.7 eV based on lattice-matched triple-junction solar cells. In this work, an appropriate model is used to investigate the SMR based power rating of CPV modules. This model uses SMARTS2 spectral irradiances, measured multi-junction cell EQEs and the two-diode model to derive the power output of CPV modules at various spectral conditions. In this manner, the measurement uncertainty introduced by the SMR filtering of ± 3.0% for the four investigated cell types is quantified to - 2.4 % and + 1.7 % in worst case. Power ratings at different test labs and/or different test periods can have a deviation of 3.9 % in worst case due to the SMR filtering approach. The outcome of the investigations can be summarized as follows.

1. Lattice-matched triple-junction component cells are suitable for SMR filtering based CPV module power ratings - even though the CPV modules are using other types of multi-junction cells.
2. A SMR filtering of ± 3 % around unity leads to reasonable measurement uncertainties.

ACKNOWLEDGMENTS

The authors express their sincere thanks to Christian Gueymard for developing SMARTS2. The authors are thankful to the companies Sharp and Soitec for publishing the EQE of their solar cells. Furthermore, the authors thank Matt Muller and the IEC TC82 WG7 power rating team for the work on the IEC standard 62670-3. Last but not least we are much obliged to all the colleagues of the "III-V-Epitaxy and Solar Cell" department for their support and discussions. This work has been partially supported by the European Union under grant agreements no 640873 from the Horizon 2020 research and innovation program within the project CPVMatch.

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