Component Cell Based Restriction of Spectral Conditions and the Impact on CPV Module Power Rating

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Abstract

One approach to consider the prevailing spectral conditions when performing CPV module power ratings according to the standard IEC 62670-3 is based on spectral matching ratios (SMR) determined by the means of component cell sensors. In this work, an uncertainty analysis of the SMR approach is performed based on a dataset of spectral irradiances created with SMARTS2. Using these illumination spectra the respective efficiencies of multi-junction solar cells with different cell architectures are calculated. These efficiencies were used to analyze the influence of different component cell sensors and SMR filtering methods. The three main findings of this work are as follows. First, component cells based on the lattice-matched triple-junction (LM3J) cell are suitable for restricting spectral conditions and are qualified for the standardized power rating of CPV modules - even if the CPV module is using multi-junction cells other than LM3J. Second, a filtering of all three SMRs with ±3.0 % of unity results in the worst case scenario in an underestimation of -1.7 % and overestimation of +2.4 % compared to AM1.5d efficiency. Third, there is no benefit in matching the component cells to the module cell in respect to the measurement uncertainty.

1. Introduction

In Concentrator Photovoltaics (CPV), optical elements are used to focus the sun light onto small III-V multi-junction solar cells. The type of III-V multi-junction solar cell used in CPV modules is rather diverse. Different multi-junction cell concepts with efficiencies above 40 % are industrially available and even more cell concepts are under development in different laboratories. Philipps et al. list the most important III-V cell concepts in [1]. All multi-junction concepts have in common that they have a higher sensitivity to spectral conditions compared to single-junction cells. This is why a standardized method to rate the power output of PV modules using multi-junction solar cells must take the prevailing spectral conditions into account.

A standardized method to rate the power output of CPV modules is defined in the standard IEC 62670-3. In addition, the standard rating conditions are defined in IEC 62670-1. According to that, the spectral conditions for rating of CPV modules must be equivalent to AM1.5d (IEC 60904-3). The approach recommended in IEC 62670-3 to determine the prevailing spectral conditions is based on component cell sensors [2,3,4]. Component cell sensors use sub cells of III-V multi-junction solar cells which have the same optical characteristics as the multi-junction solar cell, but have the electrical characteristics of the single sub cell. In this manner, the integral values of the effective spectral irradiance in distinct wavelength regions are determined. These integral values are used to calculate so called spectral matching ratios (SMR) [2,4,5]. The SMRs quantify the difference of the prevailing spectral conditions to reference spectral conditions for a certain set of solar cells. These differences are given as percentage deviation from unity as SMR values of unity indicate the same solar cell short circuit current generation as for the AM1.5d spectral condition. Two questions are of importance for SMR based power ratings of CPV modules. First, which types of multi-junction solar cells are recommendable as basis for the component cell sensor? Second, which deviations of SMR values from unity are acceptable to achieve a low uncertainty for the power rating? The current IEC 62670-3 power rating standard recommends SMR values within ±3.0 % and component cell sensor on the basis of lattice-matched triple-junction solar cell structures [3,6].

These two questions are investigated in this work in a theoretical manner. First results of this work have been presented in [7]. A representative dataset of prevailing spectral conditions which may occur during CPV module power ratings is calculated with SMARTS2 [8]. The experimental External Quantum Efficiency (EQE) data of various III-V multi-junction solar cells are used to calculate the short-circuit current density J_{SC} of the respective sub cells at these prevailing spectral conditions. The investigated multi-junction solar cells are a four-junction cell [9,10], as well as a lattice-matched [11], an inverted metamorphic [12,13] and an upright metamorphic triple-junction solar cell [14]. The calculated J_{SC} of the sub cells are then used as input for an equivalent-circuit-model of the multi-junction cell. The circuit model is based on the one-diode-model to calculate the electrical characteristic of the solar cell at the prevailing spectral conditions. The advantage of this approach is the focus on the impact of the spectral conditions on the CPV module power output without the influence of lens temperature issues, for instance. The outcome of the investigation in this work is an estimation of the uncertainty for the rated power output when using different SMR filtering approaches and different types of component cell sensors.

2. Representative Dataset of Spectral Conditions

For the investigations in this work, as the first step, a representative dataset of spectral irradiance conditions is generated. The spectral irradiance on earth is mainly influenced by the air mass (AM), aerosol optical depth (AOD) and the precipitable water (PW) [15]. There are other parameters with less influence on spectral irradiance as air pressure and circum solar irradiance, for instance, which are kept constant in this work. Therefore, in this work the variability of spectral irradiance on the earth surface is reproduced by varying AOD, PW and AM. The influence of AM, AOD and PW on spectral irradiance in this work is calculated with the simulation software SMARTS2 [8]. All input parameters for SMARTS2 are set as defined for the AM1.5d reference spectrum [16]. AOD, PW and AM are then varied independently of each other in a broad range.

For that reason, AM is varied between 1 and 12, PW between 0 and 12 and AOD between 0 and 0.6. The step size of AM for the variation was 0.04 up to AM 2 and 0.06 up to AM 4 and 0.1 up to AM 12. For AOD the step size was 0.01. For PW the step size was 0.01 up to PW 0.3, 0.1 between PW 0.3 and PW 4, 0.5 between PW 4 and PW 12. The reason for the change in step size for AM and PW is the much stronger decrease of direct normal irradiance (DNI) for changes at small AM and PW values rather than for high ones. A dataset of 740,000 spectra is created in this manner including all possible combinations of AM, AOD and PW.

As this dataset of spectral irradiances should represent spectral conditions which may occur during power ratings of CPV modules, only AOD, PW and AM combinations are kept which correspond to spectral irradiances with an integral DNI value between 700 and 1100 W/m². This is the DNI range recommended in IEC 62670-3. 125,000 of these datasets fulfill the DNI criteria. In Figure 1, AOD, PW and AM values of the dataset representative of spectral conditions occurring during CPV module power ratings are shown as a histogram. Furthermore, Figure 1 shows the histogram of AOD, PW, and AM remaining after filtering for spectral matching ratios within ±10 and ±3 % of unity; using the spectral response data of a state of the art lattice-matched component cell sensor from Black Photon [3].

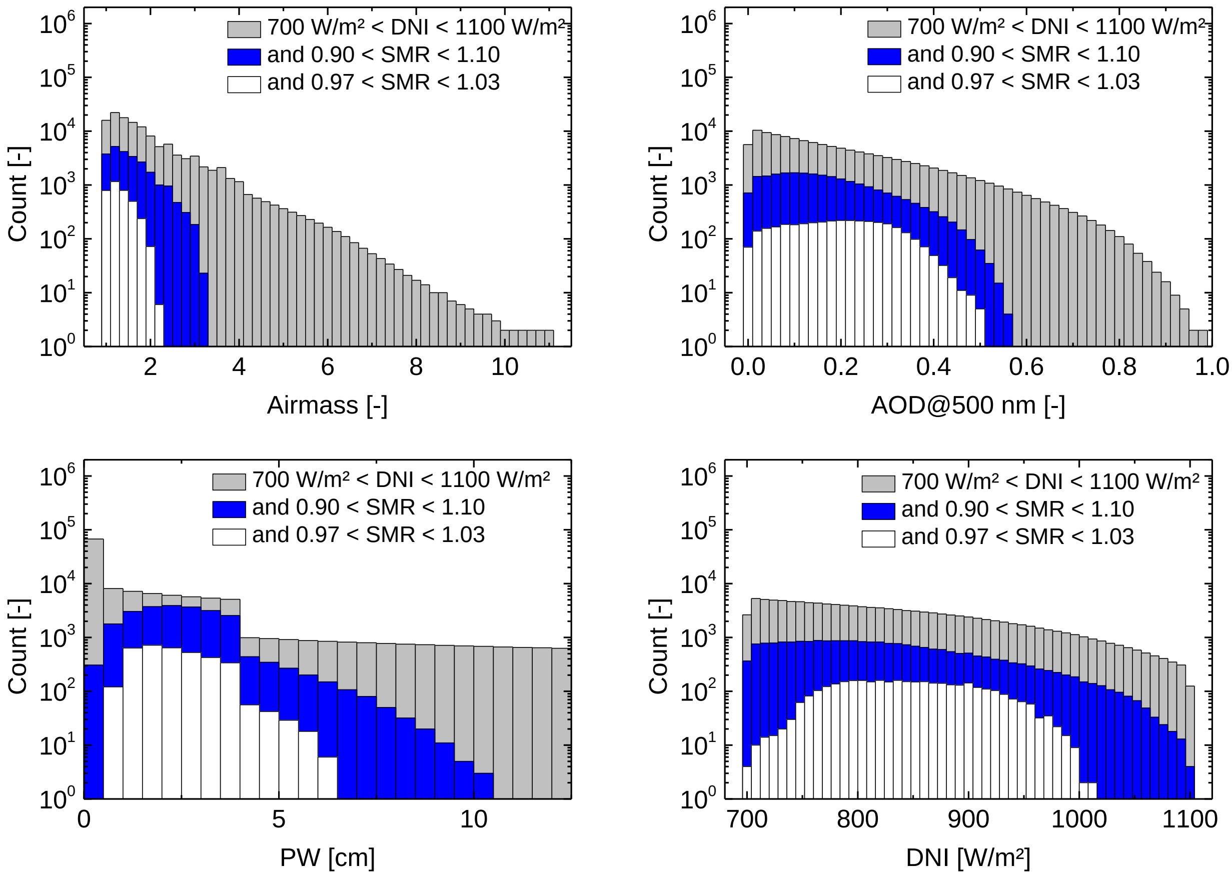

Figure 1: Air mass (AM), aerosol optical depth at 500 nm (AOD), and precipitable water (PW) used as input for SMARTS2 and the corresponding calculated direct normal irradiance (DNI) are shown as histogram plots. The graphs show the count of each input parameter using all combinations of AM, AOD and PW. Each graph shows the histogram of spectral irradiances with a DNI between 700 and 1100 W/m². Additionally, histograms of the input values are shown, which are remaining after filtering for SMR ±10.0 and ±3.0 % of unity using a state of the art lattice-matched 3J component cell sensor. Note that the count axes are in logarithmic scale.

3. Investigated Multi-Junction Solar Cells

The specimens investigated in this work are lattice-matched (LM3J) [11], upright metamorphic (UMM3J) [14] and inverted metamorphic triple-junction (IMM3J) solar cells [12] as well as four-junction (4J) [9] solar cells. These cells cover most of the current state of the art for multi-junction solar cells and have proven their high potential in efficiency [1,10,13]. Table 1 lists the band gap energy and the excess current of the sub cells calculated for AM1.5d spectral conditions. Figure 2 shows the EQE of the cells used within this work. The EQEs are measured at 25 °C cell temperature using a grating monochromator setup [17].

A theoretical approach is assuming band pass filters with 100 % in the sub bands corresponding to the sub cells of lattice-matched triple-junction solar cells. This approach is named 100 % LM3J in the following. The theoretical 100 % LM3J is defined in IEC 62670-3 and is proposed to be used to calculate SMR values when using spectral irradiance measurement devices other than component cells. The top subcell of the 100 % LM3J absorbs 100 % of the photon from 370 to 650 nm, the middle subcell from 650 nm to 870 and the bottom sub cell from 870 nm to 1650 nm. Furthermore, the investigations in this work include two variations of LM3J. $LM3J_{top}$ has ~5 % lower top cell current generation and $LM3J_{mid}$ has ~5 % higher top cell current generation. In this manner, the current limiting sub cell of LM3J is varied.

Cell type	**Band gap energy in eV**				**Excess current of sub cell**			
	1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Black Photon	1.9	1.4	0.7	-	0.0%	9.3%	54.7%	-
LM3J	1.9	1.4	0.7	-	0.3%	0.0%	40.7%	-
$LM3J_{top}$	1.9	1.4	0.7	-	0.0%	4.9%	47.6%	-
$LM3J_{mid}$	1.9	1.4	0.7	-	5.3%	0.0%	40.7%	-
UMM3J	1.7	1.4	0.7		6.1%	0.1%	0.0%	-
IMM3J	1.9	1.4	1		0.0%	4.7%	8.1%	-
100%EQE	1.9	1.4	0.7	-	0.5%	0.0%	77.1%	-
4J	1.9	1.4	1.1	0.7	3.0%	0.0%	5.5%	5.6%

Table 1: Band gap energy and excess current in the respective sub cells calculated for exactly AM1.5d spectral conditions. Sub cell 1 has the highest band gap energy of the sub cells.

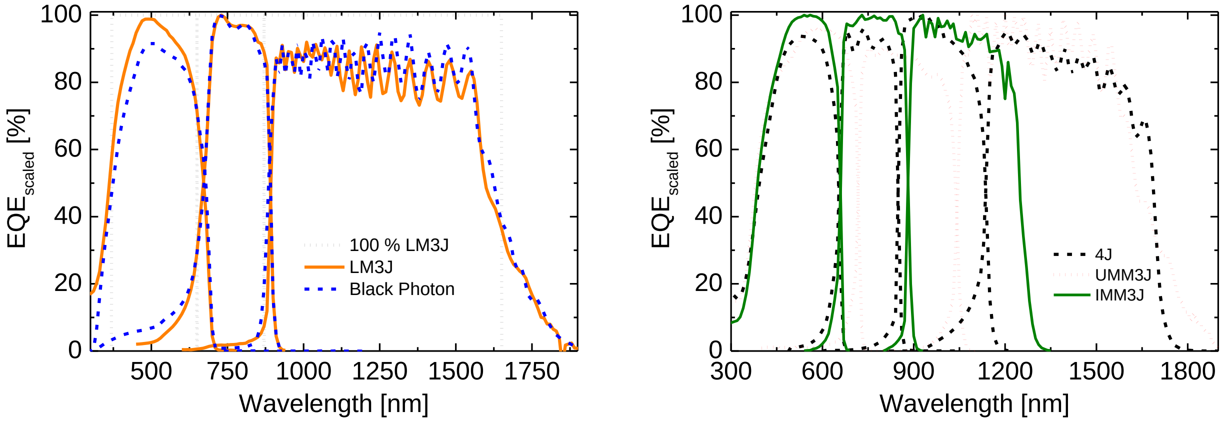

Figure 2: External quantum efficiency (EQE) of the investigated cell concepts. The EQEs of all cell concepts are scaled in a manner that the sub cell with highest absolute EQE is normalized to 100 %. The same normalization factor is applied to the other sub cells, so that the relative difference between the sub cells is unchanged.

Additionally in Figure 2 the EQE of a Black Photon component cell sensor is shown [3]. The EQE of the Black Photon sensor includes the absorption and reflection of its cover glass. The EQEs shown in Figure 2 are all scaled in a manner that 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. The absolute value of the applied EQE is negligible for the investigation within this work, only the relative value in respect to the other sub cells is important. The EQEs shown in Figure 2 are used to calculate SMR values and power outputs of CPV modules. In this manner, the investigated solar cell concepts are used twice, first, as component cell sensor and, second, as the cells within CPV modules.

4. Evaluation of Various Cell Types as Basis of Component Cell Sensors

4.1 Restricting the variation of spectral conditions using component cell sensors

The power rating of CPV modules demands for standardized and thus comparable measurement conditions. The measurement conditions especially have to be comparable, when the measurements are done at different sites and/or at different test periods. Therefore, restricting the variation of prevailing spectral conditions for the power rating of CPV devices is mandatory. The most common approach to limit the variation of spectral conditions is based on spectral matching ratios (SMR) calculated from component cell data. In this work the SMR values are calculated following [2,4,5] and as defined in the appendix. SMR values of unity indicate the same current generation in the sub cells as would be for an AM1.5d spectral irradiance. Note, that SMR values do not carry any information about absolute intensity. Thus, AM1.5d similar spectral irradiances retrieved from a filtering for SMR values close to unity can have a DNI other than 900 W/m².

In respect to the filtering for spectral conditions when performing the power rating of CPV devices there are two counteracting requirements: In order to achieve spectral conditions as close as possible to AM1.5d the filtering for SMR values needs to be as tight as possible around unity. On the other hand, a tight filtering will lead to a significant reduction of usable measurements and even might lead to the case where after filtering too few measurements are left. Consequently the filters defined for a power rating should be tight enough to assure proximity to AM1.5d spectral conditions but also loose enough to allow for a reasonable number of measurements to be used in performing the power rating. In the current IEC 62670-3 power rating standard a filtering for all SMRs of ±3.0 % around unity is recommended. At least for the location of Fraunhofer ISE (Freiburg, Germany) this filter level seems reasonable. In 2014, A SMR filtering of ±3.0 % around unity reduces the amount of sunny clear sky days (usable for a power rating of CPV modules; DNI > 700 W/m², DNI/GNI > 0.8) from 147 to 89 days. These 89 days with SMR of ±3.0 % around unity are nearly evenly spread between February and October. Therefore, in most periods of this year a power rating of CPV devices following IEC 62670-3 could have been reasonably performed. Figure 3 shows the percentage of measurement days left as a function of the filter limit for the three SMR values; as determined with a lattice-matched triple-junction component cell sensor (for the year 2014 in Freiburg, Germany).

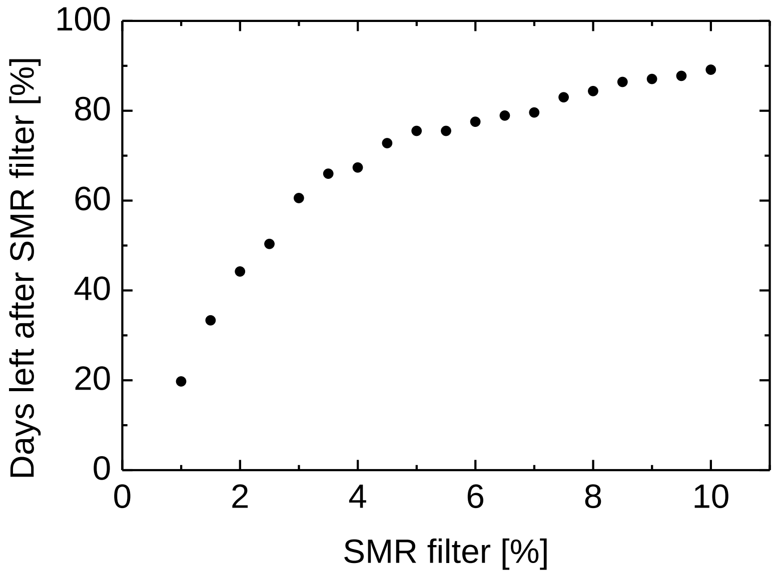

Figure 3: Percentage of sunny clear sky days left after SMR filtering. One year of data gathered at Fraunhofer ISE in Freiburg is used. For an SMR filter for SMR_{12}, SMR_{13} and SMR_{23} of ±3.0 % around unity, 61 % of the measurement days are left. The measurement days left for power rating are nearly evenly spread over a period of nine months from February until October. The total number of clear sky days in 2014 in Freiburg was 147.

4.2 SMR filtering of the representative dataset using component cell sensor

In section 2 above, the calculation of a dataset of spectral conditions representative for CPV applications using SMARTS2 has been described. This dataset consists of 125,000 spectral irradiances with a DNI above 700 W/m². Together with the EQE data of the specimens described in section 3, the short-circuit densities J_{SC} of all sub cells are calculated. These J_{SC} values are used to calculate spectral matching ratios (SMR) following [2,4,5] and as defined in the appendix. The current IEC 62670-3 power rating draft standard recommends a filtering of all SMR values of ±3.0 % around unity. If SMR values are calculated from each of the 125,000 spectral irradiances in the representative dataset and filters are applied to only accept SMR values within ±3.0 % of unity, most of the spectral irradiances drop out. Table 2 shows the number of spectral conditions remaining after applying the SMR filter for the different component cell structures. Less than 5 % of the spectral conditions are left for all cell types. For the 4J component cell sensor the least spectral conditions are left, whereas for the UMM3J component cell sensor the most spectra remain. The reason for this is that the four-junction cell splits the spectral irradiance into four wavelength bands and is therefore more restrictive against variations in the spectral conditions compared to the triple-junction component sensors. The reason for the higher number of spectral conditions left when filtering with UMM3J component cells is that the middle cell (cell with second highest band gap energy) absorbs photons also between 900 and 1000 nm. In this wavelength range water vapor absorption strongly occurs. That's why in this case two sub cells are affected by PW compared to the lattice-matched triple-junction cell types where only the cell with the lowest band gap is affected. Therefore, UMM3J cells do not strongly separate the PW influence in the respective sub cells. In consequence, a much wider variation of PW is remaining after filtering with UMM3J component cells. However, the question is, what is the impact on rated efficiency when considering if the datasets are filtered for SMR using different types of components cells?

	UMM3J	Black Photon	100%EQE	LM3J	IMM3J	4J
Number	5885	3543	3250	3164	3032	3012
Ratio	4.6%	2.8%	2.5%	2.5%	2.4%	2.3%

Table 2: The table shows the number of spectral conditions remaining after applying an SMR filter of ±3.0 % around unity using different types of component cells in absolute numbers as well as in percentage.

4.3 Influence on the rated efficiency of CPV modules

Each of the 125,000 spectral irradiances with a DNI between 700 and 1100 W/m², see Figure 1, is now used to calculate a power output representative for CPV modules. These powers are calculated using an equivalent-circuit-model of the multi-junction cell based on the one-diode-model. The J_{SC} values of the sub cells, which were calculated with the EQE of each multi-junction solar cell and with the spectral irradiances calculated with SMARTS2, are now used as input value for the one-diode-model. The influence of the optical elements of CPV modules on the power output is neglected in this approach. The non-uniformity of the incident irradiance on solar cell surface is not considered as well as the chromatic aberration and the temperature dependence of the spectral transmission function of the optical element. Therefore, detailed investigation about the impact of these effects on the measurement uncertainty of CPV module power rating has to be part of future work.

The J_{SC} are multiplied with a factor of 500. An increased sun light concentration of 500, which is common for High CPV application, is simulated in this manner. The dark saturation current density J_0 as input for the one-diode-model are calculated as described in [18]. In [18] the J_0 are calculated taking into account the band gap energies and the radiative recombination only.

Figure 4 shows the histogram of the calculated normalized efficiency for the four solar cell types: 4J, LM3J, UMM3J and IMM3J. The efficiencies for each cell type are normalized to the efficiency of the corresponding cell calculated for an AM1.5d spectral irradiance (IEC 60904-3). The efficiencies shown in Figure 4 are the values left after filtering for DNI (700 – 1100 W/m²) and when additionally filtering for two SMR ranges (0.90 – 1.10 and 0.97 - 1.03). The Black Photon sensor is used for SMR filtering. In the case of filtering for DNI only, the LM3J cell shows the highest deviation between minimum and maximum efficiency of 66 % whereas the UMM3J cell shows the lowest deviation of 48 %. The maximum efficiency of the LM3J is about 8.6 percent higher compared to its AM1.5d efficiency. In comparison, the maximum efficiency of the other three cell types is 3.5 % (UMM3J), 2.4 % (IMM3J) and 1.9 % (4J) higher than their AM1.5d efficiency, due to the better sub cell current matching at AM1.5d reference conditions. If additionally to the DNI filtering, a SMR filter is applied, the deviation in efficiency is significantly reduced.

The deviation between the minimum and the maximum efficiency (min-max-deviation) is reduced to around 9.3 % with SMR ±10.0 % and 3.8 % with SMR ±3.0 % for all four cell types. The mean efficiency comes close to the efficiency at AM1.5d reference conditions the tighter the SMR filtering is. For SMR ±10.0 % filtering, the mean values of all four cell types are already within 1 % of the AM1.5d reference efficiency. The results for the mean efficiency can be interpreted as follows: If test labs measure the CPV modules at a huge variety of spectral conditions with evenly distributed SMR values within ±10.0 % of unity, the mean efficiencies could be close to the efficiency at reference conditions. In contrast to this, the result for the min-max-deviation can be used as estimation of maximum uncertainty to be expected from the SMR filtering: If a test lab only measures at one distinct spectral condition with SMR values still within ±10.0 % of unity and another test lab only measures at different spectral conditions, the efficiencies of the two test labs can differ by a worst case of 9.3 % for SMR ±10.0 % filtering and 3.8 % for SMR ±3.0 % filtering. Therefore, the min-max-deviation is the more robust measure for addressing the uncertainty of the power rating procedure as compared to the mean values. Thus, the min-max-deviation will be reported in the following only.

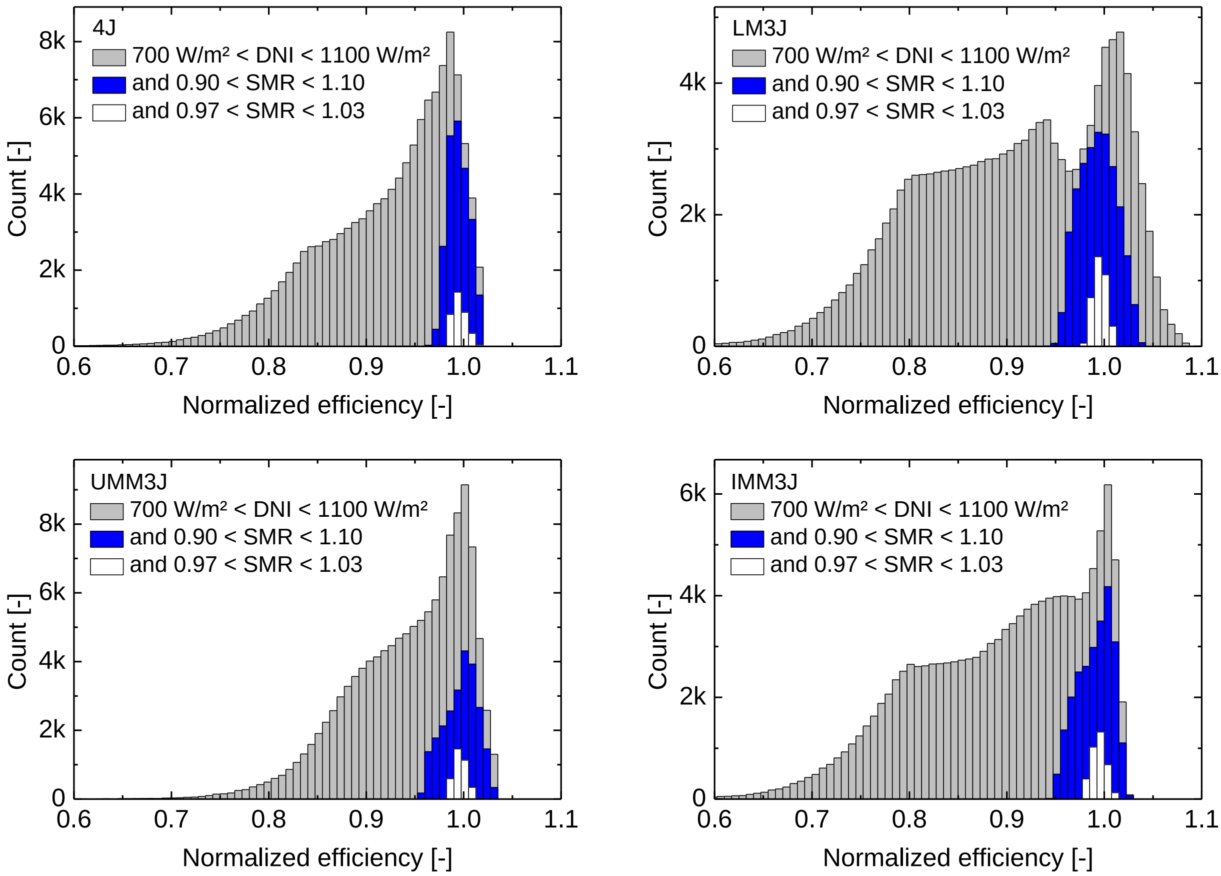

Figure 4: Efficiency of a four-junction (4J), lattice-matched (LM3J), upright metamorphic (UMM3J) and inverted metamorphic (IMM3J) triple-junction solar cell. The efficiencies are shown with filtering for DNI and additionally with SMR filtering using a Black Photon component cell sensor. The SMR filtering is done for SMR values within ±3 % and ±10 % of unity.

Table 3 summarizes the min-max-deviations after SMR filtering for ±3.0 % around unity using different types of component cell sensors when measuring the power output of CPV modules with different cell types. The min-max-deviations are given rather than mean values or standard deviation because the min-max-deviations represent the worst case. The mean values and standard deviations, even if calculated for the representative spectra dataset, may not be representative for specific test durations or locations: The calculated representative spectra dataset consists of possible spectral conditions, more or less evenly distributed. This scenario is not very likely to occur in reality for measurements sequences at a distinct location and for a limited time period.

The lowest min-max-deviation shown in Table 3 is found when using the 4J component cell sensor. This is due to the most pronounced reduction of spectral conditions with this type of component cells, whereas the UMM3J sensor has the highest overall min-max-deviation of up to 7.2 %. The reason for this is the much wider remaining variety in spectral irradiance when using UMM3J, as also discussed in the previous section. Interestingly, the lowest min-max-deviation and the lowest standard deviations are not found for the component cell sensor with the same cell type as used in the CPV module, even when neglecting the results of the 4J component cell sensor.

Therefore, the results lead to an important conclusion that there is no significant advantage of using component cell sensors made of the same type of cells as used in the CPV modules for performing a power rating. Furthermore, these investigations show that LM3J cells are well suited in limiting the variety of spectral conditions in order to realize a repeatable and accurate power rating at different locations and different test periods.

Table 3 shows also the min-max-deviations for two cell types called $LM3J_{top}$ and $LM3J_{mid}$. The EQE of these two cells is the same as of the cell LM3J, but the top sub cell EQE and thus current of $LM3J_{top}$ is reduced by ~5 % whereas the top sub cell EQE / current of LM3J$_{mid}$ is increased by ~5 %. In this manner, the relative shape of the EQE is not changed, but the current limiting sub cell is varied. Furthermore, the SMR values calculated with LM3J, LM3J$_{top}$ and LM3J$_{mid}$ are identical.

The min-max-deviations of LM3J$_{top}$ are nearly the same as of LM3J, whereas for LM3J$_{mid}$ both the min-max-deviations are increased. The reason for this originates from the impact of PW, AOD and AM on spectral irradiance. All three parameters change the spectral irradiance, mainly in wavelength regions outside the middle sub cell. Therefore, variations of the spectral irradiance by PW, AOD and AM change the integral value of the spectral irradiance i.e. DNI but have a minor impact on the current of the middle sub cell. If the middle sub cell is the current limiting than the current output of the multi-junction cell is changed less than expected from the change of the DNI value. That is why it happens that the DNI is varying but the current and power output of LM3J$_{mid}$ remains constant. However, in this case the efficiency of LM3J$_{mid}$ is varying. In cases where sub cells other than the middle sub cell are limiting the current, the power output is varying with variations in DNI and the variation in efficiency is less pronounced. This investigation reveals that the current matching of the sub cells can have a higher impact on the measurement uncertainty of rated module power output as compared to using different types of component cells for SMR filtering.

		Celltype used for efficiency calculation					
		LM3J	LM3J$_{top}$	LM3J$_{mid}$	UMM3J	IMM3J	4J
Sensor for SMR filtering	Black Photon	3.8%	3.8%	5.2%	3.5%	3.8%	3.6%
	LM3J	3.5%	3.8%	4.8%	3.2%	3.8%	3.4%
	LM3Jtop	3.5%	3.8%	4.8%	3.2%	3.8%	3.4%
	LM3Jmid	3.5%	3.8%	4.8%	3.2%	3.8%	3.4%
	UMM3J	4.6%	3.2%	7.2%	3.8%	3.3%	4.0%
	IMM3J	4.1%	4.4%	5.4%	3.2%	4.3%	3.6%
	100%EQE	3.5%	3.6%	4.7%	3.2%	3.6%	3.4%
	4J	3.3%	2.5%	5.0%	2.9%	2.7%	3.4%
	Limiting Cell	1 & 2	1	2	2 & 3	1	2

Table 3: Min-max-deviation of efficiency using different type of component cell sensors and a SMR filtering of ±3.0% around unity. The values with black background indicate the highest deviations for a distinct cell type. The last row gives the current limiting cell at AM1.5d spectral irradiance conditions.

5. Evaluation of SMR filtering

The power rating of CPV modules at standardized spectral conditions using SMR filtering is always a trade-off between tight filtering for low measurement uncertainty and wide filtering for short measurement completion. In the following, the question is discussed in which manner a wider or tighter SMR filtering changes the uncertainty of the power rating. For this investigation the SMR and efficiency values calculated as described in section 4 are used. However, in the following the SMR values are calculated using the EQE of the Black Photon sensor only.

Figure 5 shows the upper and lower limit of module efficiency as a function of SMR filtering criteria for the investigated cell types. Note, that these upper and lower limits for SMR filtering of ±3.0 % are already used to calculate the min-max-deviation in Table 3. In contrast to the min-max-deviation value, the separate presentation of the results as an upper and lower efficiency limit shows the range of possible absolute efficiency values. Thus it represents the efficiency values possibly measured at test labs when using SMR filtering within their rating procedure. In contrast to spectra simulated in this paper, the spectral conditions during a real outdoor power rating period are typically not evenly distributed within the SMR filtering range. It is possible to complete outdoor measurements at the SMR boundary limits. Therefore, the upper and lower efficiency limits discussed in the following are more realistic representation of the measurement uncertainty occurring during real world power ratings (compared to the mean efficiencies and the standard deviations). For instance, the mean efficiency calculated in this work are deviating by less than 1 % from the AM1.5d efficiencies for all cell types and SMR filtering between 1 and 10 %. This is only valid if the mean SMR values measured during the rating procedures are close to unity.

Figure 5 shows the efficiency limits as a function of SMR filtering for all three SMR values determined with a Black Photon lattice-matched 3J component cell sensor. The efficiencies shown in Figure 5 are normalized to the efficiency at AM1.5d reference spectral conditions. Figure 5 shows that when filtering for all three SMR values for unity ±3.0 % the rated module efficiency can be overestimated by +2.5 % and underestimated by –2.9 % for all six investigated multi-junction solar cells architectures. This means that in the worst case scenario the efficiencies rated by two test labs or in two different test periods with SMR values close to the SMR filtering limits of ±3.0 % can differ by up to 5.4 %. If we neglected $LM3J_{mid}$ which has an artificially created excess current in the top, the rated efficiency could be overestimated by +1.7 % and underestimated by -2.4 %. Thus, the efficiencies for two test labs or two different test periods can differ by 3.8 % in worst case.

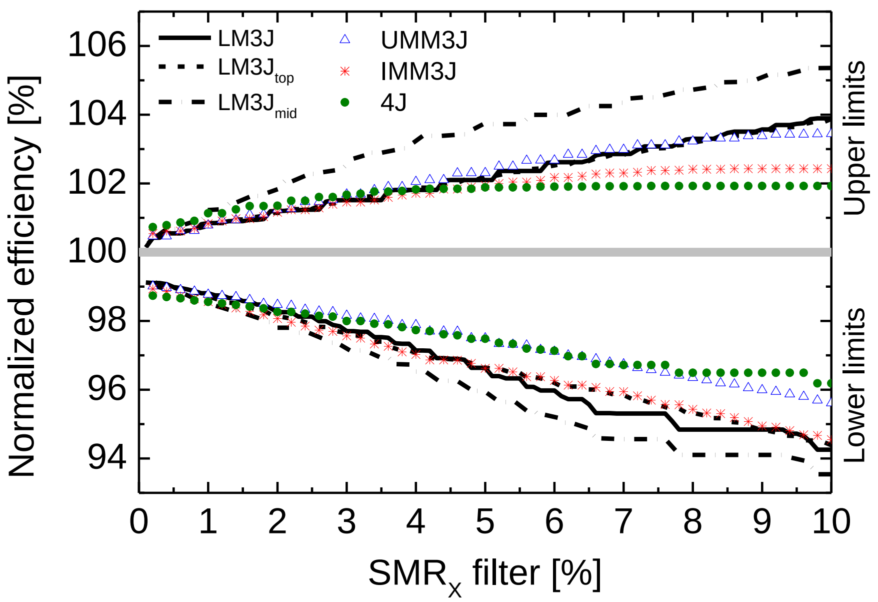

Figure 5: Upper and lower limit of the normalized efficiency of the investigated multi-junction solar cells as a function of SMR filtering. The efficiencies are normalized to the module efficiency at AM1.5d reference spectral conditions. The SMR values are calculated with the Black Photon lattice-matched components cells. The graph show the upper and lower limits of the efficiencies left after SMR filtering. The same SMR filter percentage value is used for all three SMR values.

6. Conclusions

A standardized method to determine the efficiency and power output of CPV modules in a repeatable and comparable way demands to take into account the prevailing spectral condition during the measurements. One approach to consider the spectral conditions is to calculate spectral matching ratios (SMR) based in component cell sensor readings. These SMR values are then restricted to around unity. SMRs of unity indicate spectral conditions similar to AM1.5d. In this work, component cell sensors based on different multi-junction solar cell architectures are investigated for their suitability for restricting the spectral conditions for a power rating of CPV devices. For this reason, a representative dataset of spectral irradiances which may occur during test periods of CPV power rating is created using SMARTS2. This dataset includes over 125,000 spectral irradiances. For each of these irradiances SMR values are calculated and used for restricting the prevailing spectral conditions in order to generate the same power output as for AM1.5d spectral conditions. Furthermore, the efficiency of several different multi-junction solar cells are calculated for each of these spectral irradiances remaining after filtering. The main findings of the investigations are:

1. Lattice-matched triple-junction (LM3J) component cells are suitable for limiting the spectral conditions and are qualified for standardized power ratings of CPV modules. No significant decrease in uncertainty of the rated power is found, if the CPV module is using multi-junction cell types other than LM3J.
2. A filtering of all three SMRs within ±3.0 % of unity is sufficient. The deviation from AM1.5d efficiency which are representative for CPV modules using realistic multi-junction solar cells were determined to +1.7 % and -2.4 % for the worst case scenario.
3. The deviation from AM1.5d efficiency can be further reduced if the SMR values are evenly distributed within the SMR filter boundaries.
4. There is no benefit in matching the component cells to the module cell in respect to the measurement uncertainty.

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Appendix

Definition of SMR values:

The spectral matching ratios SMR in this work are defined by the following equation:

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

whereas i and j assign distinct sub cells in the multi-junction solar cell.

In this manner, for a multi-junction solar cell with n sub cells n^2 SMR values can be calculated as presented in the following matrix:

$$SMR(i,j) = \begin{bmatrix} SMR(1,1) & \cdots & SMR(n,1) \\ \vdots & \ddots & \vdots \\ SMR(1,n) & \cdots & SMR(n,n) \end{bmatrix}$$

In this work we define the SMR values in the matrix as follows: each sub cell in a multi-junction solar cell is assigned a number in the ordering of their band gap energy E_g starting with 1. The sub cell with the highest E_g has the lowest number and the sub cell with the lowest E_g has the highest number. All SMR in the main diagonal of the matrix where i equals j have a value of 1. All SMR above the main diagonal can be calculated from the value below the main diagonal with SMR(j,i) = 1/SMR(i,j). The number of SMR values below the main diagonal is $(n^2-n)/2$. For a lattice-matched triple-junction solar cell the matrix of SMR values is as follows:

$SMR(i,j) =$

$$\begin{bmatrix} SMR(1,1) & SMR(2,1) & SMR(3,1) \\ SMR(1,2) & SMR(2,2) & SMR(3,2) \\ SMR(1,3) & SMR(2,3) & SMR(3,3) \end{bmatrix} = \begin{bmatrix} 1 & SMR(1,2)^{-1} & SMR(1,3)^{-1} \\ SMR(1,2) & 1 & SMR(2,3)^{-1} \\ SMR(1,3) & SMR(2,3) & 1 \end{bmatrix} =$$

$$\begin{bmatrix} 1 & {SMR_{12}}^{-1} & {SMR_{13}}^{-1} \\ SMR_{12} & 1 & {SMR_{23}}^{-1} \\ SMR_{13} & SMR_{23} & 1 \end{bmatrix}$$

Whereas 1 is the GaInP top sub cell, 2 the GaInAs middle and 3 three the Ge bottom sub cell in the lattice-matched triple-junction solar cell.

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