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RESEARCH ARTICLE

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Low-cost outdoor spectral irradiances determination and its application on Concentrator Photovoltaic module power rating and energy yield calculation

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Abstract

In this work, a method to calculate the aerosol content in the atmosphere and the prevailing spectral irradiance of the sunlight is introduced. This method does not aim for low measurement uncertainty but for cost effectiveness and does not require sophisticated equipment. The bases of the method are the clear sky direct normal irradiance (DNI) and a look-up table calculated with the software tool SMARTS2. The ratio of clear sky DNI to the prevailing DNI in combination with the look-up table allows the determination of aerosol optical depth (AOD), spectral matching ratios (SMR), and spectral irradiances. Besides the prevailing DNI, the following ambient condition parameters are required: Air pressure, relative humidity, and ambient temperature. This means a weather station and a pyrheliometer are sufficient for the determination of the prevailing spectral irradiance. Obviously, this method cannot guarantee the same accuracy as conventional spectral irradiance measurement methods (e.g., using a spectroradiometer). However, in this work, we demonstrate the potential of this new method as a fall-back strategy for missing spectral irradiance data. This method is worth using when (C)PV module power output data needs to be evaluated in dependence of the composition of the spectral irradiance, but no regular spectral irradiance data are available. In this paper, the AOD and SMR values determined with the introduced method are compared to measurement data with common measurement devices demonstrating a satisfying agreement. The spectral irradiances calculated with this method are successfully tested for using as the basis for energy yield calculations and for the determination of the CPV module power output at Concentrator Standard Conditions according to IEC 62670-1.

KEYWORDS
AOD, CPV, energy yield, multijunction solar cells, spectral irradiance, tandem solar cells

1 | INTRODUCTION

The power output of multijunction solar cells typically shows a significant dependence on the composition of the sunlight's spectral irradiance.[1] Therefore, the understanding of the behaviour of the (C)PV module power output and energy yield at prevailing ambient conditions in different seasons and locations demands for spectral irradiance data. However, these data are not available in all cases. The reason is the necessity of expensive equipment as a spectroradiometer or component cell sensors, for instance. For this reason, we have developed a cost-effective method that does not demand for sophisticated equipment. This method only requires the readings of a weather station and of a pyrheliometer, as relative humidity, air pressure, ambient temperature, and direct normal irradiance (DNI) are the input parameters used. From these parameters, aerosol optical depth (AOD[2]), spectral matching ratios (SMR[3–5]), and spectral irradiances can be calculated. Obviously, the outcome of this method is not as accurate as obtaining these values from commonly used measurement devices. However, the values calculated with this new method are still an adequate approach if there is no other source of spectral irradiance data available.

In this work, we introduce and explain this method in detail. The method is based on the calculation of the clear sky DNI ratio and an AOD look-up table calculated using the software tool SMARTS2.[6] In the look-up table, a single AOD value is retrieved as a function of clear sky DNI ratio, precipitable water (PW), and air mass (AM). Clear sky DNI ratio is the ratio of prevailing DNI to DNI calculated with SMARTS2 with AOD and PW set to zero. The parameters PW and AM can be calculated using commonly available methods.[6–8] Once AM, AOD, clear sky DNI ratio, and PW are available, the prevailing spectral irradiance can be calculated using SMARTS2 as in Faine et al.[1]

The calculated AOD values are compared to measured data in two different locations: Freiburg, Germany, and New Delhi, India. Moreover, the spectral irradiances derived from the calculated AOD using SMARTS2 are tested by comparing measured SMR with SMR derived from the calculated spectral irradiance. The correlation between measured and calculated data is assessed by statistical quantities such as the coefficient of determination (R^2) and the mean absolute error (MAE).

Furthermore, the spectral irradiances calculated with this method are evaluated for their suitability as basis for energy yield calculations and for determination of the CPV module power output at Concentrator Standard Conditions.[5,9] For this reason, two different types of CPV modules are used as specimen: BSQ D280 and AZUR C3PV CPV modules.

2 | THE CLEAR SKY DNI METHODOLOGY TO RETRIEVE AOD

The method to calculate the AOD and spectral irradiances from the readings of a pyrheliometer and of a weather station according to this work is described in the following. The main idea behind this method is that the sunlight that hits the Earth's surface is attenuated on its way through the atmosphere by well know processes.[2] The three main processes are Rayleigh scattering by molecules, Mie scattering of the sunlight by microscale particles (aerosols), and the absorption of sunlight by PW.[1,2] These effects are proven to be calculated accurately by software tools like SMARTS2,[6] for instance. However, distinct input parameters need to be available for the correct calculation of spectral irradiances with SMARTS2. The main input parameters are the AM, AOD at 500 nm (AOD_{500nm}), and PW. As AM can be calculated from time, latitude, and longitude, PW from relative humidity, air pressure, and ambient temperature, the main aim of the method is to obtain a value representative for AOD_{500nm}. The method is based on the following steps where the final step is the calculation of spectral irradiances:

1. Calculation of DNI at clear sky conditions $DNI_{ClearSky}$ ($AOD_{500nm} = 0$, $PW = 0$, other settings as defined in IEC 60904-3[10]) as a function of AM using SMARTS2 (Figure 1, left)
2. Calculation of a look-up table with SMARTS2: AOD as a function of PW, AM and ratio of prevailing DNI to DNI at clear sky conditions ($DNI_{prev}/DNI_{ClearSky}$)
3. Calculation of AM, for every measured DNI and PW value: If PW is not measured it can be calculated from ambient temperature, relative humidity, and air pressure with equation (1)
4. Calculation of $DNI_{ClearSky}$ and $DNI_{prev}/DNI_{ClearSky}$ for specific outdoor measurements.
5. Interpolating $AOD_{500nm,calc}$ from the look-up table by using the parameters calculated in 3 and 4, which are PW, AM, and $DNI_{prev}/DNI_{ClearSky}$
6. Calculation of spectral irradiance with SMARTS2 using $AOD_{500nm,calc}$, PW_{calc}, and AM as input parameters. Other parameters set as in IEC 60904-3.[10]

Step 1 is the calculation of $DNI_{ClearSky}$ as a function of AM as shown in Figure 1 (left). $DNI_{ClearSky}$ is determined as the integral value of the spectral irradiances calculated with SMARTS2. The input parameters for SMARTS2 are set as defined for the AM1.5d reference conditions as listed in IEC 60904-3.[10] However, AOD_{500nm} and PW are set to a value of zero and AM is varied. The air pressure is set to 1013 mBar as this is sea level standard atmospheric pressure. If the method is used at a location where the air pressure differs strongly from this value, then it is recommended to adjust the air pressure.

Step 2 is the calculation of a look-up table with AOD_{500nm} as a function of AM, PW and $DNI_{prev}/DNI_{ClearSky}$ using SMARTS2. The $DNI_{ClearSky}$ value is taken from step 1, which is plotted in Figure 1 (left), for the respective AM value. The DNI_{prev} values are calculated as the integral value of spectral irradiances, which are calculated with SMARTS2. The input parameters are set as defined in IEC 60904-3,[10]; however, AOD, PW, and AM are varied independently in a three dimensional matrix: AOD between 0 and 1 in steps of 0.05, PW between 0 and 12 in steps of 0.4, and AM between 1 and 12 in steps of 0.5. In this manner, 14,974 spectral irradiances and thus 14,974 $DNI_{prev}/$

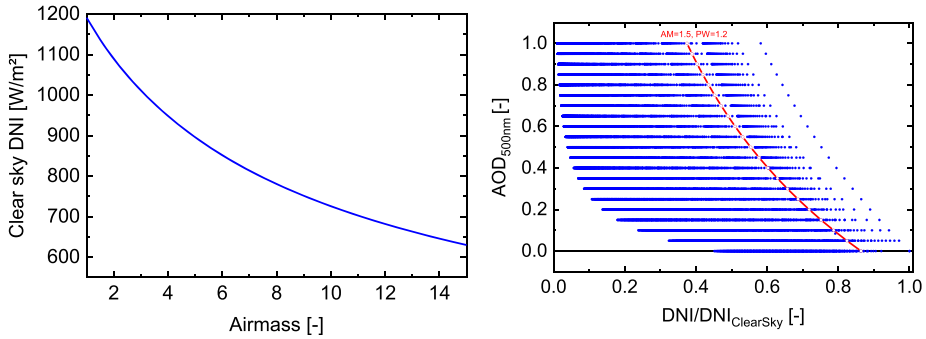


FIGURE 1 Left: $DNI_{ClearSky}$ as a function of air mass calculated as the integral value of spectral irradiances. The spectral irradiances have been calculated with the software tool SMARTS2 with the same input parameters as defined in IEC 60904-3,[10] but the parameters AOD_{500nm} and PW are set to zero. Right: Graphical representation of the calculated look-up table: AOD_{500nm} as a function of $DNI_{prev}/DNI_{ClearSky}$. Variation of $DNI_{prev}/DNI_{ClearSky}$ values for distinct AOD values are resulting from varying air mass and PW input parameters simultaneously. The red line highlights the correlation of AOD and $DNI_{prev}/DNI_{ClearSky}$ for an air mass value of 1.5 and a PW value of 1.2.

$DNI_{ClearSky}$ values are calculated. Figure 1 (right) shows the calculated $DNI_{prev}/DNI_{ClearSky}$ values versus AOD_{500nm}. Obviously, $DNI_{prev}/DNI_{ClearSky}$ versus AOD_{500nm} is not a unique function. For this reason, additionally PW and AM have to be known to retrieve a distinct AOD_{500nm} value for a specific $DNI_{prev}/DNI_{ClearSky}$ value. Figure 1 (right) exemplarily shows this for an AM of 1.5 and a PW of 1.2 (red line).

Step 3 is measuring the actual, prevailing DNI_{prev} with a pyrheliometer and calculation of AM. The value for PW could be measured directly if appropriate equipment is available or calculated using Equation (1) as described in Garrison and Adler.[7]

$$PW_{calc} = 0.19 \cdot \left(\frac{216.7 \cdot h_{rel} \cdot e_s}{T_{amb}}\right) \cdot \frac{p_0}{p_{00}} + 0.20 \text{ with } e_s = 10^{\left(8.43 - \frac{1827.2}{T_{amb}} - \frac{71208.2}{T_{amb}^2}\right)} \quad (1)$$

where p_{00} is the yearly mean air pressure at sea level (1013.25 mbar), p_0 the yearly mean air pressure at the location, h_{rel} is the relative humidity, and T_{amb} the ambient temperature at the location. The value of AM is calculated using the equations in a previous work.[12]

Step 4 is dividing the measured DNI with the value $DNI_{ClearSky}$ corresponding to the prevailing AM as in Figure 1 left. The resulting value of $DNI_{prev}/DNI_{ClearSky}$ is then used together with the values determined for the prevailing PW and the calculated AM to derive a value for the prevailing AOD_{500nm} in step 5. Finally, in the last step the prevailing spectral irradiance is calculated with the software tool SMARTS2 by using $AOD_{500nm,calc}$, PW_{calc}, and AM as input parameters.

3 | EXPERIMENTAL EVALUATION OF THE METHOD

The method to calculate the AOD from pyrheliometer and weather station readings as described in the previous section is evaluated in the following. The PW values used as input are calculated with Equation (1). A comparison of calculated AOD_{500nm} values against measured AOD_{500nm} values is performed for two locations. In Freiburg, Germany, the AOD_{500nm} were directly measured with a Prede POM-01 Skyradiometer, and in New Delhi, India, they were extracted from the Aeronet Database.[11] In Freiburg the Skyradiometer, pyrheliometer, and the weather station are within a few metres distance (coordinates: 48.0095 N, 7.8327 E); however, in New Delhi, India, a distance of around 25 km is present between the closest Aeronet location (coordinates: 28.5885 N, 77.2216 E) and the location of the pyrheliometer and the weather station (coordinates: 28.5034 N, 77.4632 E). Figure 2 shows the comparison of calculated and measured AOD as correlation plots. In the legend of the graph the R^2 and the MAE are given as statistical measures for the agreement of calculation and measurement. Figure 2 (left) shows the correlation that has been found in Freiburg for data measured between February and October 2018. In Figure 2 (right), the correlation is shown for the location in India for 10 days between April and May 2018. The linear fits in Figure 2 show R^2 values of 0.78 (left) and of 0.85 (right). The MAE between calculated and measured data are calculated to be 0.042 (Freiburg) and 0.243 (New Delhi). The MAE is calculated as given in Equation (2).

$$\text{MAE} = \frac{\sum_{i=1}^{n} |y_i - x_i|}{n} \quad (2)$$

where n is the total number of measured values, y_i the measured, and x_i the calculated value. The R^2 and the MAE show a nonperfect but satisfying agreement of measured and calculated AOD data. In this manner, the AOD values calculated with the introduced method are not appropriate to completely replace existing methods to determine AOD values. However, the method could be valuable as a fall-back strategy if there is no equipment available for AOD determination and if long term trends and average values are more important as for example in energy yield calculations.

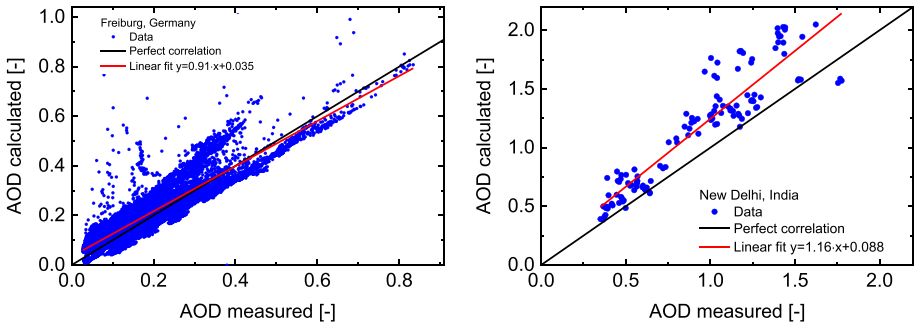


FIGURE 2 Calculated AOD values as a function of AOD values measured in Freiburg, Germany, and New Delhi, India. The graphs show as black lines the perfect correlation of calculated and measured AOD data and as red lines linear fits to the data. The linear fits have R^2 values of 0.78 (left) and of 0.85 (right). The MAE between calculated and measured data are calculated to 0.042 (Freiburg) and 0.243 (New Delhi). Note: measured AOD values in Freiburg have been derived from nearly 1 year (February to October 2012) of Prede POM-01 readings whereas the values in New Delhi have been taken from the Aeronet Database (10 days in April and May 2018).

4 | APPLICATION OF THE METHOD TO CALCULATE SPECTRAL IRRADIANCE DATA AND SMR

In the previous section, the simplified determination of the AOD_{500nm} values has been successfully demonstrated yielding a reasonable accuracy. However, the idea of the method is to quantify the prevailing spectral irradiance conditions as close as possible with the smallest effort necessary. Full spectral irradiances that potentially match the real ones under varying meteorological conditions can be retrieved. However, in this work, we just focus on checking the retrieved spectral irradiances in certain wavelength ranges rather than each wavelength one by one. For this reason, so called SMR[3–5] are used. SMR values quantify the balance of the irradiance that is available in distinct wavelength ranges in comparison to the balance of irradiance which would occur if the spectral irradiance shape would be equivalent to AM1.5d.[12] The wavelength ranges which are typically used are the following: 300–600 nm, 600–900 nm, and 900–1800 nm.[5] The idea of these wavelength ranges is that the one up to 600 nm mainly captures the influence of AM and AOD, whereas the one from 900 onwards mainly represents the impact of PW. For the determination of the SMR values typically so called component cell sensors are used.[13] The used component cells have spectral responses that mostly match the above listed wavelength ranges. The output readings of the component cell sensor are three short-circuit currents (I_{SC}). These current values can also be calculated from spectral irradiances by using the spectral response of the component cells rather than measuring the output current of the component cells. In both cases, the SMR values are calculated according to Equation (3) as defined in the IEC standard 62670-3.[5]

$$SMR_{12} = (I_{SC,1}/I_{SC,2})/(I_{SC,1,AM1.5d}/I_{SC,2,AM1.5d}) \text{ and} \quad (3)$$
$$SMR_{23} = (I_{SC,2}/I_{SC,3})/(I_{SC,2,AM1.5d}/I_{SC,3,AM1.5d})$$

where $I_{SC,1}$ is the I_{SC} of sub cell 1, $I_{SC,2}$ of sub cell 2, and $I_{SC,3}$ of sub cell 3 under the prevailing spectral irradiance and $I_{SC,1,AM1.5d}$, $I_{SC,2,AM1.5d}$, and $I_{SC,3,AM1.5d}$ are the I_{SC} of the respective sub cell under the AM1.5d reference spectrum according to IEC standard 60904-3.

SMR values as defined in Equation (3) can be derived from spectral irradiances (together with spectral response data) or from so called component cell sensors.[13] In this work, SMR values are measured in Freiburg, Germany, using one component cell for each of the three wavelength ranges mentioned above. The measured SMR values are compared to SMR values calculated from spectral irradiances using the spectral response of the sensor. In this work, the spectral response of component cells with band gaps of 1.9, 1.4, and 0.7 eV have been used (corresponding with lattice-matched triple-junction cells).[3] The spectral irradiance used for this calculation are the ones calculated by SMARTS2 based on the AOD_{500nm} values determined as proposed in this work (Section 3). Figure 3 shows the resulting correlation plots of measured SMR values and SMR values derived from spectral irradiances calculated based on the method proposed in Section 3. Figure 3 (left) shows the SMR_{12} value and right the SMR_{23} value. The SMR_{12} values mainly represent the impact of the daily variation of AM and the impact of AOD, whereas SMR_{23} values show the impact of PW on spectral irradiance. It is typical that the variation of SMR_{12} values is much more pronounced than that of the SMR_{23} value. The R^2 and MAE (Equation 2) as statistical measures of the correlation of measured and calculated values are as follows: for SMR_{12} R^2 is 0.87 and MAE is 0.027, whereas for SMR_{23} R^2 is 0.73 and MAE 0.048. Both R^2 and MAE show an imperfect but satisfying agreement of calculated and measured values. In this manner, the same conclusion as in the previous section can be drawn: The spectral irradiances calculated with the introduced method are not appropriate to replace existing methods to determine spectral irradiances (or SMR values). However, the method serves well as a fall-back strategy if there is no equipment available for spectral irradiance and/or SMR value determination.

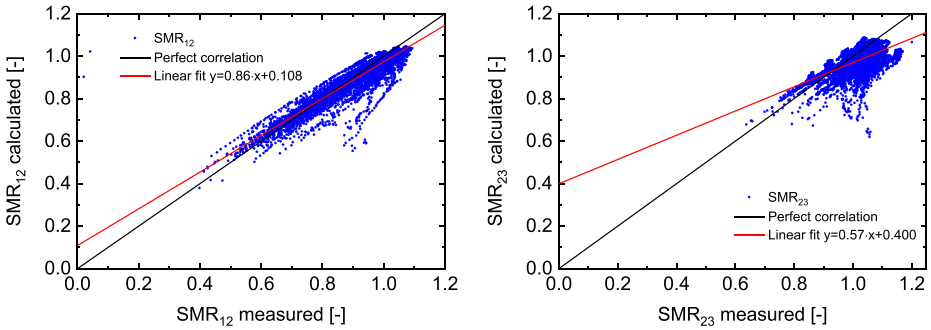
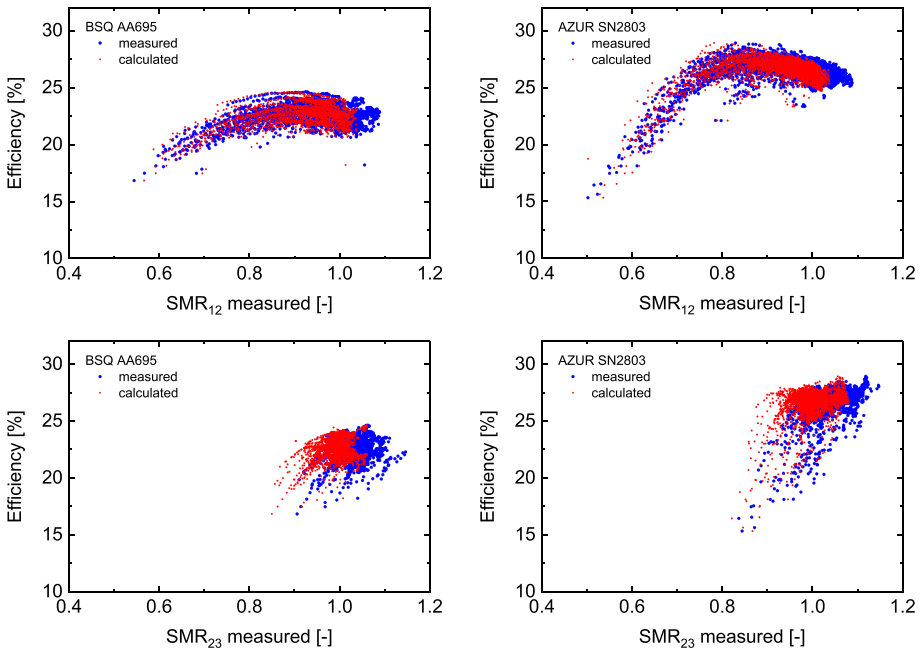


FIGURE 3 Correlation plots of calculated SMR values versus measured SMR values. The graph shows as black lines the perfect correlation of calculated and measured AOD data and as red lines linear fits to the data. The linear fits have R^2 values of 0.87 (left) and 0.73 (right). The MAEs between calculated and measured data are 0.027 (left) and 0.048 (right). Note: the SMR values are measured during the measurement period in Freiburg, Germany, in (09/2017 to 11/2018).

FIGURE 4 Efficiency of the modules BSQ D280 (SN AA695) and AZUR C3PV (SN 2803) as a function of measured and calculated SMR values. The efficiency values and SMR values are derived from measurement in Freiburg, Germany, in the period of 09/2017 to 11/2019. Data recorded at DNI to GNI ratios above 0.8 and ambient temperatures between 15°C and 25°C has been used only.



5 | APPLICATION OF THE METHOD FOR THE EVALUATION OF THE PERFORMANCE OF CPV MODULES USING MULTIJUNCTION SOLAR CELLS

The SMR values derived from the spectral irradiances calculated using the method described in Section 3 can have two exemplarily applications as input parameters for energy yield calculation and for performing power ratings. These two applications are discussed using the power output measurements performed on one BSQ D280 and one AZUR C3PV CPV-Modul in Freiburg, Germany, in the time period of 09/2017 to 11/2019. Together with the power output of the CPV modules, also SMR values are measured using a component cell sensor.[13] Figure 4 shows the electrical efficiency of the two CPV modules as a function of SMR_{12} and SMR_{23}. Figure 4 (left) shows the graph for the BSQ and right for the AZUR module as a comparison of SMR value derived from component cell sensor readings (blue) and SMR derived from spectral irradiances calculated using the method described in Section 3 (red). Data recorded at DNI to GNI ratios above 0.8 and ambient temperatures between 15 and 25°C has been used only. It can be seen in Figure 4 that the dependence of efficiency on SMR_{12} or SMR_{23} value is not a perfect match when calculated or measured SMR values are used. However, the general trend and the SMR values at which the efficiency peaks are similar. The peak position of the efficiency is connected to the SMR value where the sub cells in the tandem cells are current matched, whereas the decrease in efficiency away from these SMR values are resulting from spectral irradiances which cause an increasing current mismatch in the sub cells. This effect is specifically of importance for the accurate energy yield calculation of (C)PV modules, which use tandem cells. One option to consider this effect is to use SMR values as input parameter of the energy yield model. In this manner, the calculated SMR values seem

Module	Mean efficiency with standard deviation		
	SMR range unlimited	SMR_{meas} within ±3% of unity	SMR_{calc} within ±3% of unity
AZUR	26.54 ± 1.15	26.27 ± 0.63	26.14 ± 0.59
BSQ	22.57 ± 0.95	22.63 ± 0.51	22.57 ± 0.68

TABLE 1 Mean efficiency values of module AZUR SN2803 and BSQ AA695 in Freiburg, Germany, with and w/o SMR filtering

to be well suited to consider this effect in energy yield models. However, a detailed uncertainty evaluation of this will be part of future work.

Besides the determination of input parameters for the energy yield modelling of multijunction cell based (C)PV modules, their power rating also requires them for the consideration of the prevailing spectral irradiance conditions. The IEC standard 62670-3 specifies the use of SMR values for this consideration. Strictly speaking, IEC 62670-3 requests filtering out the SMR values beyond ±3% of unity, where unity means AM1.5d IEC 60904-3 equivalent spectral conditions. This filtering has been tested by using the electrical efficiency values measured together with SMR values as shown in Figure 4 for one BSQ and one AZUR CPV module. The resulting efficiency values together with their standard deviation before and after filter for SMR values to be within ±3% of unity are shown in Table 1. Similar to Figure 4, data recorded at DNI to GNI ratios above 0.8 and ambient temperatures between 15°C and 25°C has been used only. The SMR filtering has been done with the measured SMR values (SMR_{meas}) and with the calculated SMR values (SMR_{calc}), respectively. The dataset created by filtering for SMR_{calc} consist of 1556 (AZUR) and 1419 (BSQ) datapoints, whereas the dataset created by filtering for SMR_{meas} consist of 849 (AZUR) and 557 (BSQ) datapoints. The intersection of both datasets filtered for SMR_{meas} and SMR_{calc} consists of 409 (AZUR) and 272 (BSQ) datapoint. However, Table 1 shows that the mean values without and with filtering for SMR does not change significantly for the two modules at the location in Freiburg, Germany. However, the standard deviation of the efficiency values decreased strongly when applying the SMR filtering criterion. Furthermore, the standard deviation decreased in a nearly similar magnitude when using the calculated SMR values. In this manner, the initial results show that that it could be possible to use the SMR values calculated with the method introduced in this paper to perform the SMR filtering as requested in IEC 62670-3. Note: the filtering with the calculated SMR values has been tested in this work in Freiburg, Germany, only. Therefore, the method has to be proved at a different location separately.

6 | CONCLUSION

In this paper, a method to calculate the AOD, the spectral irradiance, and the SMR from pyrheliometer and weather station readings is introduced. The method uses the ratio of prevailing DNI to clear sky DNI values together with PW and AM as parameters to extract the prevailing AOD from a look-up table. The look-up table is calculated with the software tool SMARTS2. AOD, PW, and AM values are varied in the maximum range allowed by SMARTS2 to calculate spectral irradiances and the DNI to clear sky DNI ratio from their integral values. In this manner, the look-up table provides AOD_{500nm} as a function of $DNI/DNI_{ClearSky}$, PW, and AM. The PW values in this work have been calculated from relative humidity, air pressure, and ambient temperature. In this manner, a pyrheliometer and a weather station are sufficient rather than an expensive spectroradiometer, for instance.

The accuracy of the calculated AOD_{500nm} values and of the calculated spectral irradiances has been successfully tested by comparing these with measured AOD_{500nm} and SMR values. The calculated AOD values have been compared to measured AOD value at a location in Germany and in India with a satisfying agreement quantified by R^2 and MAE values. Furthermore, spectral irradiances have been calculated using the calculated AOD_{500nm} values as input parameters. The calculated spectral irradiances have been compared to the prevailing spectral irradiances using SMR values. The satisfying correlation of measured and calculated SMR values is proven with R^2 values of 0.87 (SMR_{12}), 0.73 (SMR_{23}) and MAE values of 0.027 (SMR_{12}) and 0.049 (SMR_{23}), respectively. In this manner, the method has been demonstrated to provide useful AOD and spectral irradiance data, however, not for the reason to substitute conventional methods to determine AOD and spectral irradiance data. The method finds its application as a fall-back strategy if no conventional methods are applicable due to missing equipment.

Furthermore, the SMR values determined with the method described in this paper have been tested and can be an option to obtain input parameters for energy yield modelling and for SMR filtering as requested for CPV module power rating according to IEC 62670-3. It has been shown that the calculated SMR values describe the dependence of CPV module power output on spectral irradiance composition in the same manner as the SMR values measured with a component cells sensors. Finally, the calculated SMR values have been used to perform the SMR filtering as requested in IEC standard 62670-3. This filtering is necessary to be close to AM1.5d IEC 60904-3 spectral conditions for the power rating at concentrator standard conditions. In this work, it has been shown that the calculated SMR values provide equivalent rated efficiency results as the measured SMR values do.

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DATA AVAILABILITY STATEMENT

Research data are not shared.

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