Evaluation of different indicators for representing solar spectral variation

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***Abstract*—In studies analyzing the performance of photovoltaic (PV) modules, average photon energy (APE) is often used as an indicator for the effect of solar spectral variation on PV module performance, as it is said to accurately distinguish individual spectra. Especially for a-Si devices, there is a strong correlation between APE and performance. However, there can be significant variation in spectra measured at specific APE values. In this study we analyze the variation of spectra at a range of APE values, and also compare APE as an indicator of spectra to other spectral indicators, namely Blue Fraction (BF), Useful Fraction (UF), Airmass (AM) and Spectral Mismatch Factor (MMF). We compare the indicators by binning spectra at different values of each parameter, and calculating the Root-Mean-Square-Deviation (RMSD) of all spectra in the bin to the mean spectrum in the bin. Subsequently, we compare these calculated results between the different parameters**

Our results indicate that APE was found the best indicator of spectral variation, with the lowest mean RMSD over the whole range of measured data. However, BF is an almost equally good indicator, and UF and MMF also show a low mean RMSD. Airmass was found to be a quite poor indicator of spectral variation.

I. INTRODUCTION

Together with irradiance and temperature, the spectral distribution of the irradiance on photovoltaic (PV) modules is a major factor determining their performance, especially for a-Si devices. In this context, average photon energy (APE) is often used as an indicator for spectral variation, and is stated to accurately distinguish individual spectra [1]. The average photon energy offers a one dimensional representation of two dimensional spectra, and is as such much more convenient to analyze spectral effects than the measured spectra themselves.

In many studies, variation in the spectral composition was found to have significant effects on the performance of PV modules [2]–[17]. In general it is found that especially amorphous silicon thin-film PV modules are affected by variations in solar spectral irradiance, leading to a decreased performance at red-rich spectra, which are spectra with low APE values. In some of the studies, other metrics are used to identify spectral variation, such as useful fraction (UF), or spectral mismatch factor (MMF). Other indicators that are related to spectral variation are airmass (AM) and blue fraction (BF)

In this study, we analyze the suitability of APE as an indicator of PV module performance as a function of spectral variation, by calculating the variation in measured spectra at a range of APE values. Furthermore, we compare APE with other spectral indicators, namely blue fraction, airmass, useful fraction, (spectral) mismatch factor, using actual measured spectra.

II. METHODS

Over the course of 2015, over 400,000 spectra were measured at the PV test facility UPOT at the university campus of Utrecht University in Utrecht, the Netherlands [18]. At a time resolution of 30 seconds, in the wavelength range of 350-1050 nm spectral irradiance was measured with an EKO instruments MS-700 spectroradiometer. The spectroradiometer is installed due south at a tilt angle of 37°. Airmass was calculated with the Pickering model [19] from solar azimuth and zenith data reported by an EKO instruments STR-21G Sun Tracker. The facility is located at a latitude of 52.1° in a temperate maritime climate, with relatively large amounts of precipitation, high degrees of cloudcover, and as such is characterized by a large seasonal variation in solar irradiation and APE.

From the measured spectra, average photon energy was calculated as

$$APE = \frac{\int_a^b E(\lambda)d\lambda}{q\int_a^b \phi(\lambda)d\lambda} \tag{1}$$

where $E(\lambda)$ is the photon energy and $\phi(\lambda)$ is the photon flux at wavelength λ, and a and b are the limits of integration, which are in this case 350 and 1050 nm.

The blue fraction (BF) describes the fraction of irradiance that can be considered "blue" and is defined as the ratio of irradiance with a wavelength of under 650 nm to the total irradiance [20], and was thus calculated as:

$$BF = \frac{\int_a^c E(\lambda)d\lambda}{\int_a^b E(\lambda)d\lambda} \tag{2}$$

where a is 350 nm, b is 1050 nm and c is 650 nm.

The useful fraction is the ratio of irradiance between wavelengths at which a PV cell is active (i.e. non-zero spectral respnose), to the total irradiance, and is thus calculated similarly as the blue fraction. In this study, we have calculated the UF for an a-Si cell, as a-Si devices are most sensitive to changes in spectra.

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The spectral mismatch factor (as defined in IEC 60904-7 [21]) was calculated for a-Si cells as well, with c-Si as the reference technology. The mismatch factor is defined as:

$$MMF = \frac{\int_a^b E_r(\lambda) \cdot SR_r(\lambda)}{\int_a^b E_m(\lambda) \cdot SR_r(\lambda)} \cdot \frac{\int_a^b E_m(\lambda) \cdot SR_m(\lambda)}{\int_a^b E_r(\lambda) \cdot SR_m(\lambda)} \tag{3}$$

where a and b are the wavelength limits of the measurements, E_m and E_r are measured and reference spectra, and SR_m and SR_r are the spectral responses of the device under investigation and the reference device, respectively.

To show the suitability of each parameter (APE, BF, AM, UF, MMF) as indicator for unique spectra, we analyzed the variation of spectra at certain bins of each parameter, by normalizing the spectra, calculating a mean spectrum from all spectra in a bin, and then calculating the root-mean-square deviation (RMSD) of all measured spectra to this mean spectrum. The root mean square deviation of a single spectrum from the mean spectrum for the bin investigated, is calculated as:

$$RMSD = \sqrt{\frac{\sum_\lambda \left(E(\lambda) - \overline{E}(\lambda)\right)^2}{n}} \tag{4}$$

where $\overline{E}(\lambda)$ is the mean spectrum in a bin, and $E(\lambda)$ is a measured spectrum.

For each analyzed parameter, we define the minimum and maximum of the range investigated as the 1^{st} and 99^{th} percentile, and then take 30 evenly spaced and sized bins. E.g. the bin spacings and sizes were defined relative to the full range of data for each respective parameters. We then aggregate these results in plots showing the spread of observed RMSD from the mean spectrum, per parameter bin. Higher RMSDs thus indicate that for a certain parameter bin the variation in measured spectra is larger compared to lower RMSDs. Figure 1 shows, as an example, a selection of spectra measured in the APE bin of 1.88±0.012 eV (left), and the mean spectrum with one standard deviation at each measured wavelength (right) within this bin. To quantitatively compare the different spectral indicators over the full range of measurements, we calculate the mean for all RMSDs from all parameter bins.

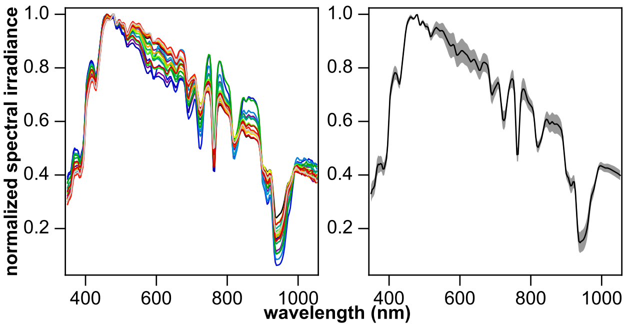

Fig. 1. Left: selection of spectra measured with APE of 1.88±0.012 eV. Right: mean spectrum for spectra with APE of 1.88±0.012 eV; the gray shaded areas indicate the standard deviation of normalized spectral irradiance at each wavelength.

III. RESULTS

A. *Quality of spectral indicators*

Figures 2-8 show the observed RMSD in spectra as a function of different spectral indicators. All figures plot the root-mean-square deviation (mean, median and ranges from 25th to 75th and from 5th to 95th percentiles) of the spectra in a bin compared to the average spectrum in this bin. Insets in the figures show the distribution of measurements of the respective indicators for the measurements' time-horizon.

As Fig. 2 shows, APE seems to be a reasonable indicator for individual spectra. The maximum mean RMSD is obtained for very low APE values, and is only 5%. Around STC (APE of 1.873 eV for the spectral range from 350-1050 nm) the mean RMSD is only around 2-3%. For blue fraction (Fig. 3), the results obtained are very similar, mean RMSDs are in the range of 2-5%. Fig. 7 shows that the mean RMSD for all spectra in all bins is 2.8 and 2.9% for APE and BF, respectively.

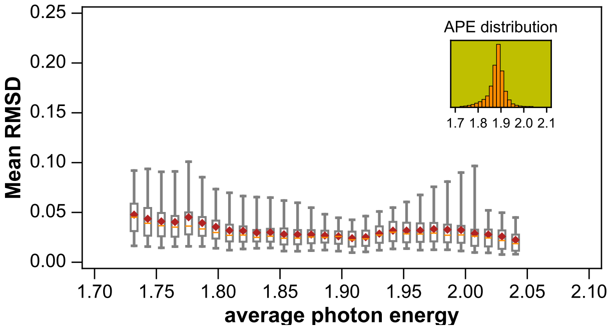

Fig. 2. Mean root-mean-square deviation of spectra from mean spectrum in different average photon energy bins. Red diamonds indicate averages of Mean RMSD, orange lines indicate medians of Mean RMSD, the boxes indicate the interquartile range, while the whiskers indicate the ranges from 5th to 95th percentiles. The inset figure shows the measured distribution of APE.

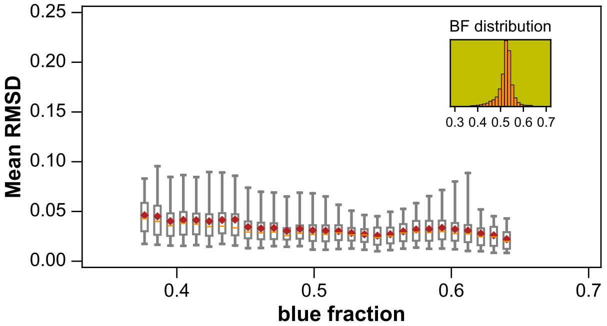

Fig. 3. Mean root-mean-square deviation of spectra from mean spectrum in different blue fraction bins. Red diamonds indicate averages of Mean RMSD, orange lines indicate medians of Mean RMSD, the boxes indicate the interquartile range, while the whiskers indicate the ranges from 5th to 95th percentiles. The inset figure shows the measured distribution of BF.

Much larger RMSDs are seen for airmass as a spectral indicator (Fig. 4). The mean RMSD ranges from 3-14%, but many spectra show much larger deviations, especially for airmass bins between 5 and 10. This is likely due to the fact

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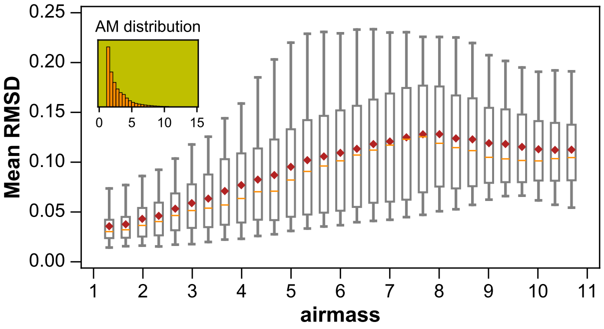

Fig. 4. Mean root-mean-square deviation of spectra from mean spectrum in different airmass bins. Red diamonds indicate averages of Mean RMSD, orange lines indicate medians of Mean RMSD, the boxes indicate the interquartile range, while the whiskers indicate the ranges from 5th to 95th percentiles. The inset figure shows the measured distribution of AM.

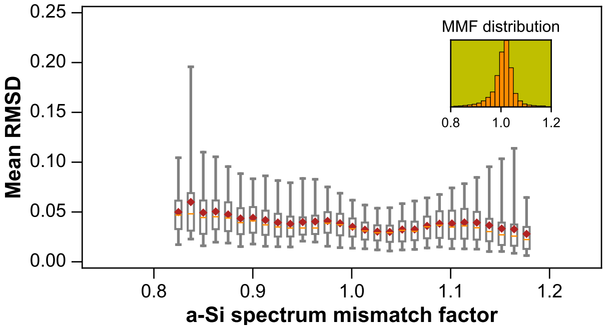

Fig. 6. Mean root-mean-square deviation of spectra from mean spectrum in different spectrum mismatch bins. Red diamonds indicate averages of Mean RMSD, orange lines indicate medians of Mean RMSD, the boxes indicate the interquartile range, while the whiskers indicate the ranges from 5th to 95th percentiles. The inset figure shows the measured distribution of MMF.

that with airmass, effects of cloudy conditions are not taken into account. For clear sky days, airmass would likely be a much better spectral indicator. Fig. 7 shows that the mean RMSD for all spectra is 5.8%.

The useful fraction is mainly used as an indicator for the effect of spectral variation on device performance. It relates the irradiance in the active wavelength-range of a device to the total irradiance. In Fig. 5 we see that UF (calculated for an a-Si cell) is a reasonable indicator for spectra, although of somewhat lower quality compared to BF and APE as Fig. 7 shows. At certain UF bins, a large range of RMSDs is observed compared to BF and APE.

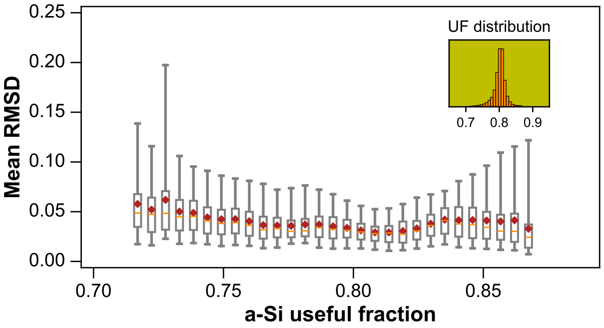

Fig. 5. Mean root-mean-square deviation of spectra from mean spectrum in different useful fraction bins. Red diamonds indicate averages of Mean RMSD, orange lines indicate medians of Mean RMSD, the boxes indicate the interquartile range, while the whiskers indicate the ranges from 5th to 95th percentiles. The inset figure shows the measured distribution of UF.

The results for the a-Si spectral mismatch factor (Fig. 6) are very similar to those observed for the UF, with generally low RMSD values, but larger deviations in general compared to APE and BF, and some especially large ranges of RMSD at specific MMF bins.

B. Comparison of spectral indicators

Figure 8 shows a comparison of the mean RMSD for each spectral indicator as a function of the percentile of observed data for each spectral indicator. It shows that for a large range of measured data, aside from airmass, most spectral indicators are of similar quality. Over a large range, APE has the lowest mean RMSD. For a large range of data (roughly 70-80%) airmass shows a much larger mean RSMD and is as such a lower quality indicator of spectra over the full range of measurements.

Shown in Fig. 7 is the overall mean RMSD for the five parameters, for all spectra in all bins. Here it becomes clear that APE has the lowest mean RMSD and thus could be considered the best indicator for spectral variation. Blue fraction is however almost as good. Airmass has more than double the RMSD, and seems to be the worst indicator for spectral variation. Useful fraction and spectral mismatch factor also have quite low mean RMSD, but are slightly higher compared to blue fraction and especially APE. Fig 9 shows the correlation of APE with the other spectral indicators, giving also an indication of the relation between RMSD for each spectral indicator.

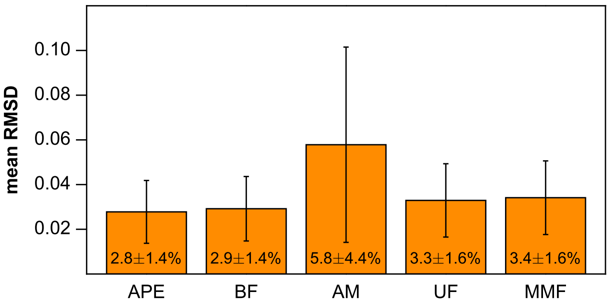

Fig. 7. Mean root-mean-square deviation of all spectra analyzed in this study, for the five spectral indicators considered. The error bars show one standard deviation from the mean.

IV. CONCLUSION AND DISCUSSIONS

In this study we aimed to analyze the variation of solar irradiance spectra as a function of varying average photon energy. APE is often used to establish the effect of solar

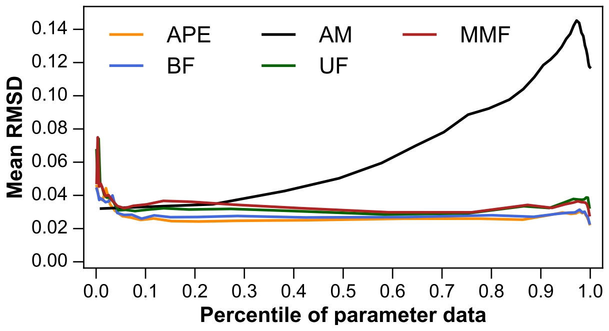

Fig. 8. Mean root-mean-square deviation of spectra from mean spectrum for all five investigated spectral indicators. The x-axis shows the percentile of data for each indicator.

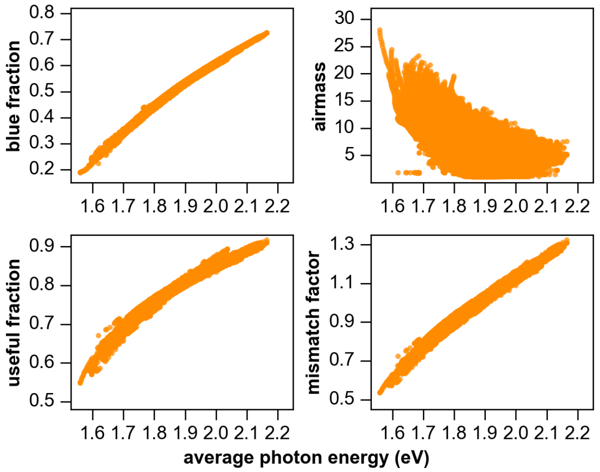

Fig. 9. Scatterplot of average photon energy with blue fraction, airmass, useful fraction and mismatch factor

spectral variation on PV module performance, and is found to have effects on especially the performance of amorphous silicon thin-film PV modules.

We found that although there can be significant variation of spectra at certain APE bins, overall APE seems to be a good indicator of different spectra. When comparing APE with other indicators of solar spectral irradiance, we see that of the considered parameters, mainly airmass underperforms in comparison to the other spectral indicators.

Our results show that average photon energy, as well as blue fraction, are the most accurate indicators for spectral variation, with a mean RMSD of 2.8±1.4% and 2.9±1.4%, respectively. Of slightly lower quality are useful fraction and spectral mismatch factor, calculated for a-Si cells (3.3±1.6% and 3.4±1.6%, respectively). Compared to the other spectral indicators, airmass does not seem to be a good indicator of unique spectra under realistic operating conditions in a location with a high number of cloudy measurements, with an RMSD of 5.8±4.4%. Although useful fraction and spectral mismatch factor more directly refer to device performance, as they are calculated with the aid of spectral response curves of the considered PV technology they are thus not more accurate, and furthermore rely on a source of data that is not available for many commercial PV modules. Therefore, we suggest that APE is used as a device-independent indicator of spectral variation and the effect of spectral variation on PV module performance. Furthermore, we recommend that this study is extended to other climatic zones to show that different cloud cover does not influence the results presented here, except for the airmass factor.

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