Spectral Binning for Energy Production Calculations and Multijunction Solar Cell Design

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Abstract

Currently, most solar cells are designed for and evaluated under standard spectra intended to represent typical spectral conditions. However, no single spectrum can capture the spectral *variability* needed for annual energy production (AEP) calculations, and this shortcoming becomes more significant for series-connected multijunction cells as the number of junctions increases. For this reason, AEP calculations are often performed on very detailed yearlong sets of data, but these pose two inherent challenges: (1) these data sets comprise thousands of data points, which appear as a scattered cloud of data when plotted against typical parameters, and are hence cumbersome to classify and compare, and (2) large sets of spectra bring with them a corresponding increase in computation or measurement time. Here we show how a large spectral set can be reduced to just a few "proxy" spectra which still retain the spectral variability information needed for AEP design and evaluation. The basic "spectral binning" methods should be extensible to a variety of multijunction device architectures. In this study, as a demonstration, the AEP of a 4-junction device is computed for both a full set of spectra and a reduced proxy set, and the results show excellent agreement for as few as 3 proxy spectra. This enables much faster (and thereby more detailed) calculations and indoor measurements, and provides a manageable way to parameterize a spectral set, essentially creating a "spectral fingerprint" which should facilitate the understanding and comparison of different sites.

1. Introduction

Because series-connected multijunction solar cells are spectrally sensitive, the spectral content of the incident light is a critical consideration. For design purposes, standard direct spectra can be developed for specific regions. For example, the ASTM G173 direct spectrum represents the spectral content of the direct spectra in the arid southwestern region of the United States [1, 2]. This is quite useful, because it ensures that a CPV system designed for a particular standard spectrum will be suitable for use in the corresponding geographic area.

However, a single design spectrum does not convey any information about the *variability* of spectra at a particular site. This variability is crucial, because it affects the annual energy production (AEP) [3-13], and thereby the levelized cost of electricity (LCOE) of a system, and may also affect the design of multijunction cells for such systems. Here we show how a set of ~50,000 spectra representing spectral conditions over the course of a year can be reduced to a much smaller set of "proxy" spectra. Our results show that, with an effective binning process, a very small set of just three proxy spectra retains enough information about spectral variability to accurately compute and design for AEP.

Such a small set of proxy spectra can greatly reduce the time needed for AEP calculations, enabling much more detailed and thorough investigations. Although in some cases it may be possible to use a full yearlong set of spectra, the time needed for computations can become prohibitive due to the large number of spectra (around 50,000 for 5-minute time increments).

A small proxy set also enables practical indoor AEP measurements [14], because a solar simulator can reasonably be adjusted to three different spectra, but not 50,000. In addition, proxy spectra can provide a spectral "fingerprint" for specific sites, facilitating site-to-site comparisons of the spectral content, spectral variation, and AEP results.

To be effective, the proxy spectra must accurately serve two purposes:

1) Solar cell design. The optimal cell designs for the full spectral set and the reduced proxy set should be nearly identical.

2) AEP prediction. For a fixed cell design, the computed annual energy production for the full spectral set and the reduced proxy set should be equal.

In a prior study [15] we presented preliminary results on the effectiveness of spectral binning for a 2-junction (2J) solar cell. Here we extend our spectral binning methods to a 4-junction (4J) cell, and evaluate the results in more detail. Although it might reasonably be supposed that more proxy spectra would be needed for 4J modeling than for 2J, we find that three proxy spectra produce excellent results for 4J cells.

2. Binning Methods

A. Binning algorithms

To reduce the original spectral set to a smaller set of N_b proxy spectra, we first bin the original spectra into N_b bins, with the i th bin containing n_i spectra, such that the spectra in each bin have similar spectral content as described below.

To test their effectiveness, spectral binning algorithms are applied to yearlong spectral sets for Golden, Colorado. These spectra are generated for 5-minute intervals with the SPCTRAL2 model [16] under clear-

sky conditions, using as input a set of atmospheric parameters measured in 2013 at NREL's Solar Radiation Research Laboratory.

We define for use as the spectral binning parameter an "equivalent photocurrent ratio" (EPR) for each spectrum, defined to be the flux of photons with wavelengths longer than a cutoff wavelength, divided by the flux of photons with wavelengths shorter than the cutoff. This parameter is similar to the "spectral mismatch ratio" (SMR) used in Reference [17] to characterize the current mismatch of multijunction solar cells inside CPV modules, and the spectral content of spectra corresponding to different sites. An EPR is similar to an SMR in that it is independent of the solar cell characteristics, and simply characterizes the relative spectral content in two spectral ranges. In this paper, the cutoff wavelength will be provided with each EPR, i.e. "EPR(1000nm)".

It should be mentioned that the exact binning parameter does not appear to be critical, as long as it correlates well with spectral variation. Two different EPR cutoffs, 1000 nm and 650 nm, were tried. The 1000 nm case roughly divides the terrestrial spectrum into a shorter-wavelength region where the most significant spectral variations occur, and a longer-wavelength region with less spectral variation. The 650 nm case is near the absorption edge for a top subcell of a typical state-of-the-art multijunction solar cell, and therefore roughly parameterizes the current mismatch between a top subcell and the underlying subcells. As we will show later, the results are very similar in both cases, suggesting that any parameter which quantifies the fundamental short- *versus* long-wavelength irradiance variations (such as the "average photon energy" for each spectrum) should also work well for spectral binning.

Once an EPR has been assigned to each spectrum, the bin boundaries need to be determined. This is done by sorting the spectra with increasing EPR, then grouping them into bins such that (as nearly as possible) the incident spectral energy for each of the bins is equal. Once again, the exact bin boundaries do not appear to be critical. Equal-energy binning allocates more bins for midday hours, and fewer for morning and evening. We have also tried binning by air mass, with fewer midday bins and more morning/evening bins, and found that this also works well.

We denote the j 'th spectrum ($j=1$ to n_i) in the i 'th bin ($i=1$ to N_b) by $\Phi_{i,j}(\lambda)$. The same i and j subscripts will be similarly applied to other parameters associated with each spectrum, including time span ($t_{i,j}$), direct normal irradiance ($\text{DNI}_{i,j}$), and temperature ($T_{i,j}$).

Using this indexing, each bin is assigned a time

$$t_i = \sum_{j=1}^{n_i} t_{i,j} \quad (1)$$

and an energy

$$E_i = \sum_{j=1}^{n_i} \text{DNI}_{i,j} t_{i,j}. \quad (2)$$

If the representative DNI for each bin is defined as

$$DNI_i = \frac{E_i}{t_i}, \quad (3)$$

then the total incident energy is conserved:

$$\sum_{i=1}^{N_b} DNI_i t_i = \sum_{i=1}^{N_b} \sum_{j=1}^{n_i} DNI_{i,j} t_{i,j}. \quad (4)$$

The proxy spectrum $\Phi_i^P(\lambda)$ for the i th bin is the time-interval-weighted average of the n_i original spectra in each bin, averaged at each wavelength:

$$\Phi_i^P(\lambda) = \frac{1}{t_i} \sum_{j=1}^{n_i} t_{i,j} \Phi_{i,j}(\lambda). \quad (5)$$

For typical data sets (with equally spaced time intervals), $t_{i,j}$ is constant, so the above equation reduces to

$$\Phi_i^P(\lambda) = \frac{1}{n_i} \sum_{j=1}^{n_i} \Phi_{i,j}(\lambda). \quad (6)$$

Equations (5) and (6) are self-consistent with equation (3); integrating $\Phi_i^P(\lambda)$ over λ also yields DNI_i (if the spectral units are $dE/d\lambda$).

Figure 1. Plot illustrating the EPR binning algorithm, for five bins. Each colored dot represents one spectrum in the original yearlong spectral set, and the solid curve indicates the cumulative energy. The vertical lines indicate the boundaries for spectral binning, and the markers represent the resulting "proxy" spectra. For this and all subsequent figures, the "original" spectral set was created by applying SPCTRAL2 to atmospheric data taken every 5 minutes during 2013 in Golden, Colorado (see text).

To help visualize and understand binning results, energy weighting can be used to assign representative parameters such as AM_i , T_i and EPR_i to each bin. (However, due to the non-linear relationship between

atmospheric spectra and these parameters, the representative atmospheric parameters for a particular bin will not, in general, exactly replicate the corresponding proxy spectrum.) Using EPR as an example:

$$\text{EPR}_i = \frac{1}{E_i} \sum_{j=1}^{n_i} \text{EPR}_{i,j} \text{DNI}_{i,j} t_{i,j}. \quad (7)$$

Figure 1 shows the result of binning the full set of ~50,000 spectra into five proxy spectra. Each colored dot in the scatter plot corresponds to one spectrum in the original yearlong spectral set, plotted as the DNI of each spectrum against the EPR. The solid line is the cumulative energy for the spectra plotted as a function of the EPR.

The vertical lines indicate the bin boundaries, determined by subdividing the total energy into N_b regions of equal total energy. The cross symbols indicate the representative DNI and EPR for each proxy spectrum. The cumulative energy vs. EPR curve shows that most of the energy in the annual spectral set is contained by the lower EPR ("blue-rich") spectra, corresponding to the central hours of each day.

Figure 2. Spectral content of the spectral set shown in Figure 1, represented as $(J_{sc,top}, J_{sc,bottom})$ pairs for an ideal 2-junction solar cell optimized for maximum energy production. The color of each dot indicates the $EPR(1000nm)$ for each of the original spectra. The dashed line indicates where the top and bottom subcells are current-matched. Squares and triangles correspond to proxy spectra created by spectral binning (see legend). The single-bin proxy spectrum for EPR-binning differs from the G173-direct spectrum (circle).

B.

Characteristics of the original and binned spectra

To evaluate the effectiveness of spectral binning, cell efficiencies and AEP values can be computed for representative model solar cells. Here we begin with a 2J cell, in order to facilitate understanding of the binning procedure and characteristics, before proceeding to the more complicated case of a 4J cell.

For convenience, the component subcells are ideal, having External Quantum Efficiencies (EQEs) equal to 1 for all above-bandgap photon energies, and no non-radiative recombination. The 1.58/0.94 eV bandgaps chosen for this 2J device maximize AEP for this spectral set.

A 2J cell is a useful starting point because the subcell photocurrents for each spectrum can be displayed on a single plot (Figure 2). Each dot corresponds to the subcell photocurrents (J_{sc}) produced by a single spectrum in the original set, and the markers provide the same information for the G173-direct reference spectrum and binned "proxy" spectra. The curved shape of the scatter plot, which becomes more top-cell

limited closer to the origin, is caused by the variations in AM, with dispersion due primarily to AOD variations. Because current-matching is such a strong driver of efficiency, the (angular) distance from the dashed current-matching line is very important, and indeed, there is a strong correlation between EPR and (J_{sc} top / J_{sc} bottom) in Figure 2.

3. Assessment of the Binning Methods

Next, we will evaluate the accuracy of spectral binning as the number of bins is increased, to see how many bins are required to adequately represent the full spectral set. We will consider four-junction cells for the remainder of this paper, because spectral sensitivity generally increases with the number of junctions.

A. Multijunction Solar Cell Design.

To determine the suitability of a small set of proxy spectra for cell design, we optimized a 4-junction cell for AEP using both the set of proxy spectra, and the full yearlong spectral set, then compared the resulting designs. The proxy spectra were once again created by applying the EPR(1000nm) binning method.

In Figure 3 we show AEP vs junction bandgaps for an ideal 4-junction solar cell, comparing the full spectral set to the proxy set. The contours show that the optimal designs obtained for the full spectral set and the proxy spectra converge rapidly as the number of bins (i.e. number of proxy spectra) is increased – a very small number of bins (~3) provides excellent accuracy.

The optimal design obtained for the G173 AM1.5 direct spectrum is also included in the plots of Figure 3, and it deviates noticeably from the optimum bandgaps obtained for the full spectral set. However, for this particular site, the difference in energy production happens to be very low ($< 0.3\%$). The same can be said for the 1-bin spectra, with an energy loss $< 0.6\%$. Although these percentages are small, they are also systematic, and represent energy gains which can be realized with proper cell and system design. Also, the Golden, Colorado location used in this example is expected to be a good match to the G173 AM1.5 direct spectrum, and the differences will be significantly larger for locations which are not as well described by the G173 spectrum.

Figure 3. Annual energy production of a 4-junction cell, plotted against the subcell bandgaps, operated under the whole yearlong spectral set (solid lines) and the proxy spectra created by spectral binning (dashed lines). For brevity, only the contours corresponding to adjacent subcells are shown. The two sets of contours are nearly identical for 3 bins (**bottom**), whereas noticeable differences can be seen if only a single bin is used (**top**). The markers correspond to the optimum design for the G173-direct reference spectrum.

B. Calculation of Annual Energy Production

Figure 4 shows how the accuracy of AEP calculations improves as the number of bins is increased. This was done by comparing the AEP computed for sets of proxy spectra (with the number of bins varied) to the AEP obtained using the full spectral set.

For EPR(1000 nm) binning, *the error falls to less than 1% as the number of bins is decreased to just three*. For more bins, the error decreases only slowly. Even though EPR(650 nm) binning should be more sensitive to current mismatches between the 1st (1.917 eV) and underlying subcells, the accuracy of the EPR method for 650 and 1000 nm is similar. This is because the EPR method for either cutoff wavelength captures the

most important spectral variations (due to AM and AOD), once again suggesting that similar results could be obtained using any binning parameter which quantifies these spectral variations.

Even though Golden, Colorado lies within the region represented by the AM1.5d G173 reference spectrum, using this reference spectrum to calculate the AEP introduces a significant error (red circle in Figure 4). A similar error is seen for a single-bin proxy spectrum, even though it is site-specific. This further motivates the use of binned spectra, rather than a single “representative” or reference spectrum, for AEP predictions.

Figure 4. The AEP error for a 4-junction device decreases rapidly as the number of bins is increased. Two different EPR cutoff wavelengths (650 and 1000 nm) are compared, and both work well. If the cell temperature is not constant, similar accuracy can be obtained if each bin is assigned its own energy-averaged temperature. The cell efficiency under the standard G173 direct spectrum can be used to estimate an AEP, but with a noticeable (and site-dependent) error.

4. Cell Temperature and other System-Dependent Factors

The use of multiple proxy spectra addresses changes in spectral content in the incident light, but CPV systems experience other variations in operating conditions. For example, the cell temperature varies daily and seasonally, as the ambient temperature, wind speed, humidity and irradiance change. In a CPV system, optical non-idealities and tracking errors can alter the spatial and spectral distribution of irradiance, and this can change the cell efficiency [18-21]. Any system-dependent factor which introduces performance variability

could motivate an additional binning dimension, or other adjustments to the binning algorithm. Here we consider the additional variability created by cell temperature variations.

In the previous sections, the results presented were obtained assuming that the cell temperature was constant at 300 K. However, an increase in operating temperature decreases the subcell voltages, and alters the subcell photocurrents and hence current-matching by decreasing the bandgaps [22-24]. It is therefore important to consider how temperature variability might affect spectral binning.

For the cell modeling done here, the difference between the cell temperature and the ambient temperature is assumed to vary linearly with DNI, reaching a maximum temperature offset of 45°C above the ambient temperature (T_{amb}) for DNI = 1000 W/m² (which is close to the highest DNI in this spectral set), as indicated in the inset of Figure 4. The bandgaps for the idealized 4J solar cell case used here vary at a rate of -0.45 meV/K, which is typical for III-V materials [25]. Each proxy spectrum is assigned an equivalent temperature T_i , given by the energy-weighted average of the temperatures for the original spectra within each bin.

We find that spectral binning continues to be effective when temperature variations are included. In Figure 4, the AEP at fixed temperature of 300K is compared with the AEP including temperature fluctuations, using the EPR(650 nm) binning. As can be seen, the accuracy is very similar to the constant-temperature case, with an error below 1% for 3 or more proxy spectra. When used for cell design (to determine the optimal bandgap combination for maximum AEP), the original spectral set can be accurately represented by three proxy spectra, similar to the case of constant temperature shown in Figure 3.

These results might have been anticipated because there is not a strong correlation between EPR and temperature. We expect that these conclusions will remain valid for sites other than Golden. In fact, the temperature excursions in Golden are large (-20°C to 35°C typically) and may therefore be near the upper limit for temperature-related errors.

5. Photon Coupling

Photon coupling (PC) in a series-connected multijunction solar cell occurs when one subcell is overdriven with respect to the others, and is therefore forward-voltage biased and can emit photons, which can be absorbed by lower bandgap subcells. Because this transfer of excess photocurrent reduces the sensitivity of series-connected multijunction cells to spectral variations [26-28], it should also reduce the errors due to spectral binning.

To see if this is the case, we added photon coupling to our 4J cell model by setting the "photon coupling factors" to non-zero values. Each photon coupling factor $\eta_{k,k+1}$ couples light emitted by junction k to the underlying junction $k+1$, and its value quantifies the ratio (photocurrent produced by photon coupling in

junction $k+1$) / (the total neutral region recombination in junction k) [28, 29]. The maximum value of $\eta_{k,k+1}$ is constrained to be slightly below 1, since a fraction of the photons must escape out the front of the solar cell [29]. Coupling factors as high as 0.9 have been experimentally demonstrated [28].

Figure 5 shows that when the coupling factor is set to 0.9 for all junctions, the AEP errors due to binning become even smaller. For the cases where the coupling factor is set to 0.9 in only one pair of contiguous junctions, the coupling between the 1st and 2nd junctions contributes most to reducing the AEP error, and the coupling between the 3rd and 4th junctions contributes the least. This is likely due to the fact that AM and AOD preferentially remove short-wavelength light from direct spectra, and this affects primarily the top-cell photocurrent.

Figure 5. Because subcell-to-subcell photon coupling reduces sensitivity to spectral variation, AEP errors become even smaller when photon coupling is added to the 4-junction cell model.

6. Effect of Clouds

The results shown so far were obtained using spectra generated under clear sky conditions (without clouds). However, clouds can complicate spectral datasets because the original spectra for partly-cloudy conditions are often recorded with their DNI reduced to the average DNI for a particular time interval.

This causes an error due to the non-linear decrease in solar cell voltage with decreasing irradiance. For example, the same cell produces less energy when operating for 1 hour under 500 W/m² than for (0.5 hour at 1000 W/m²) + (0.5 hour at 0 W/m²).

The best solution, if possible, is to split partly-cloudy timespans into two shorter timespans, each with its own spectrum: one high-DNI clear-sky spectrum, and a second, low-DNI, cloud-altered spectrum.

If this cannot be done, the resulting error can be reduced if a second binning dimension is added which sorts by DNI. This essentially preserves the integrity of the truly cloud-free spectra, and relegates the erroneous partly-cloudy spectra to low-DNI bins which have less influence on the AEP. For design purposes, another common approach is to discard spectra whose DNI values fall below a certain threshold due to clouds.

7. Conclusions

For annual energy production (AEP) design and evaluation, a single standard spectrum is inadequate because it conveys no information about spectral *variability* of any given site. At the other extreme, a complete yearlong set of spectra contains all of the necessary information, but calculations or measurements performed with this full set can be time-consuming and cumbersome. In this work we find that, with an effective binning algorithm, a small set of "proxy" spectra can capture enough information about the spectral variability of a site to adequately design for and evaluate the AEP of multijunction cells.

As a test and example, the AEP of a 4-junction device was computed for both a full set of spectra and a reduced proxy set, and excellent agreement was found for as few as 3 proxy spectra. Once established, small sets of "proxy" spectra should enable much faster (and thereby more detailed) calculations and indoor measurements, and could also serve as "spectral fingerprints" to facilitate the understanding and comparison of different sites.

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