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Comparison of solar spectral irradiance measurements using the average photon energy parameter

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Abstract

The average photon energy (*APE*) is commonly used as a means to classify solar irradiance based on the relative distribution of energy over the spectrum. Prior studies have shown a single *APE* can identify a unique spectral irradiance distribution with low standard deviation, but have not demonstrated this distribution will be the same across different geographic locations. This paper investigates this possibility by comparing the spectral distributions of global horizontal irradiance from two different locations, indexed by *APE* value. The *APE* is shown to be a strong predictor of spectral irradiance distribution for the two datasets after they are filtered to remove low irradiance data. Comparing the irradiance data from the two locations showed that the same *APE* value defines very similar distributions for global horizontal spectral irradiance recorded at the sites considered. This raises the possibility of using the *APE* value as a quality control for spectral irradiance measurements.

Keywords: Spectrum; Average photon energy; Photovoltaic

1. Introduction

1.1. Motivation

Members of the photovoltaic (PV) community are in the process of developing procedures that will rate the performance of PV modules by their lifetime energetic output rather than the instantaneous power output under a set of standardised conditions. Such 'energy rating' is being standardised in the IEC 61853 series of standards. This has resulted in the need to develop a deeper understanding of the role that the spectral response of these devices plays in their final energy yields. The acquisition of spectrally-resolved irradiance data from a number of sites across the world is an essential part of this effort. Eventually this data will be incorporated into the definition of standard climatic data sets to be used in the calculation of energy yields in parts 3 and 4 of IEC 61853.

As it is not possible to acquire spectrally resolved irradiance measurements for every location on earth, studies are being conducted to model average spectral resources over broad geographical areas (Amillo et al., 2015). To reveal meaningful trends in the data, it is convenient to be able to classify each spectrum using a single metric that can indicate the balance of long and short wavelengths relative to a reference distribution such as the standard AM1.5 spectrum. Although the same average value can be arrived at through a number of different spectral distributions, natural limits to the stochastic variability of the solar spectrum suggest a single value will describe a narrow range of distributions. Furthermore, whilst the motivation for such

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analyses is to predict the output of PV devices with specific spectral responses, it is also useful to select a metric that is independent of the spectral response of any particular technology.

1.2. Average photon energy

The 'Average Photon Energy' (*APE*) value, first proposed by Jardine et al. (2002) and Williams et al. (2003), is a popular metric amongst the PV community for describing the spectral quality of solar irradiance. This is analogous to an average wavelength value (Belluardo et al., 2013) but instead, it represents the average energy of all the photons impinging upon a target surface. The *APE* is calculated by dividing the total energy in a spectrum by the total number of photons it contains, as shown in Eq. (1). Here q [eV] is the electron charge, E_λ [W m^{-2} nm^{-1}] is the spectral irradiance at wavelength λ, and Φ_λ is the photon flux density at wavelength λ.

$$APE\ [\mathrm{eV}] = \frac{1}{q}\left(\frac{\int E_\lambda\, d\lambda}{\int \Phi_\lambda\, d\lambda}\right) \tag{1}$$

The photon flux density is in turn calculated using the Plank–Einstein relation hc/λ [J] using the formula in Eq. (2). The *APE* value is therefore independent of the absolute intensity of light at each wavelength and indicates only the averaged distribution of light across the spectrum.

$$\Phi_\lambda\ [\mathrm{photons\ m^{-2}\ s^{-1}\ nm^{-1}}] = \frac{E_\lambda}{hc/\lambda} \tag{2}$$

The *APE* value is used as a convenient means for extracting or modelling PV performance trends against large datasets of spectral irradiance. It has been used in a number of studies to examine the output of different PV technologies as a function of spectral resource (Cornaro and Andreotti, 2013; Dobbin et al., 2011; Moreno-Sáez et al., 2013; Betts et al., 2005; Norton et al., 2011; Garcia-Domingo et al., 2011; Krishnan et al., 2009; Minemoto et al., 2007). Unlike the 'Useful Fraction' (*UF*) index (Betts et al., 2004), the mismatch factor (*MM*), or the '*Z* Parameter' (Peharz et al., 2009), the *APE* is a technology-independent parameter that describes only the spectral composition of solar irradiation. Although more recent studies have highlighted shortcomings of using the *APE* as a PV performance indicator (Dirnberger et al., 2015), it still offers benefits when used as a qualitative indicator of spectral irradiance resource.

The question of whether the *APE* can be relied upon to represent a unique distribution of energies across the spectrum has been addressed by Minemoto et al. (2009, 2011). In their assessment they used global tilted spectral irradiance measurements taken over the wavelength range of 350–1050 nm. The *APE* values were calculated using Eqs. (1) and (2) and used to group the measured spectra in *APE* steps of 0.02 eV. For their particular dataset, standard deviations of up to 0.4% of the total irradiance were reported, allowing them to conclude that the *APE* is a reasonable index to describe spectral irradiance distributions used for evaluating PV performance. However, it was acknowledged that this result applied only to the dataset considered and would perhaps not hold true across different measurement sites. It is yet to be determined whether a single *APE* value will correspond to the same spectral distribution at different measurement locations. The usefulness of *APE* analyses may therefore be limited if they cannot be compared across different sites.

In this work, the authors attempt to demonstrate that the *APE* is a suitably robust metric for classifying spectral distributions by expanding the work of Minemoto et al. This is done by analysing spectral irradiance datasets from two different locations, and cross-comparing the results to understand whether *APE* analyses yield consistent results across different measurement locations.

2. Method and instrumentation

2.1. Approach

Two spectrally-resolved global horizontal irradiance (GHI) datasets have been obtained, providing data collected using different equipment at different locations, climatic conditions and times of the year. The choice of these locations was based primarily on the availability of the data and the fact that they were accompanied by detailed uncertainty analyses. The two locations have different climates and average atmospheric depths. The climatic conditions of the two locations are described in the world map of the Köppen–Geiger climate classification (Kottek et al., 2006). The climate at the JRC is classified as warm-temperate/fully humid/warm summer (Cfb), whereas the NREL site is borderline between snow/fully humid/warm summer (Dfb) and arid/steppe/cold arid (BSk). A summary of the location details, including the wavelength range of the spectral irradiance measurements and the reported spectroradiometer calibration uncertainties (U_c), is given in Table 1.

When evaluating the *APE* as an indicator of spectral irradiance distribution, the uncertainties involved in each measurement system have to be considered, not least because a cross-comparison of results is to be performed. Spectroradiometer inter-comparison campaigns (Galleano et al., 2012; Habte et al., 2014) occasionally use a 'performance statistic' (PS) (Electrotechnical Commission (IEC), 2010) to quantify the extent to which different systems agree on a measurement. This unit-less value is calculated as shown in Eq. (3) using the measurement uncertainty (U_n) of each n system along with their measurements over a given wavelength range ($M_{\lambda n}$) under a common irradiation source. A *PS* value of between −1 and +1 indicates an agreement that takes into account the standard deviation of measurements and initial calibration uncertainties. Values of *PS* falling outside these boundaries signifies an unsatisfactory level of agreement. Here, the 'performance statistic' will be used to provide a quantitative assessment