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On the uncertainty of energetic impact on the yield of different PV technologies due to varying spectral irradiance

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Abstract

Varying spectral irradiance affects performance of photovoltaic (PV) modules depending on their band gap and spectral response. Therefore, energy rating or yield prediction procedures should take into account the irradiance that is effectively available for a specific PV technology. This effective irradiance differs from broadband solar resource information first due to the different spectral sensitivity of PV devices and pyranometers, and second due to the difference between real and reference spectral distribution. The combined difference, also referred to as 'spectral impact', is to date considered in form of fixed spectral gain or loss factors applied to the broadband solar resource – if it is considered at all. Values for the monthly or annual spectral impact have been reported for several locations; however without estimates of their uncertainty. This article addresses the question of how large the uncertainty of the spectral impact is. Contributions to the uncertainty of the spectral impact are discussed, with focus on the method of determining the spectral impact by means of measured spectral irradiance and calculated spectral mismatch factor (*MM*). Using a simplified procedure, the uncertainty of spectral impact was estimated from the average spectral mismatch uncertainty. It was found to be of the same magnitude as the spectral impact itself, and dependent on the PV technology. For five single-junction PV technologies, amorphous silicon, cadmium telluride, standard crystalline silicon, high-efficiency crystalline silicon and a wide-band-gap CIGS technology, the estimated uncertainty values were 1.8%, 1.4%, 0.9%, 1.0% and 1.2%, respectively. The results were obtained from a specific measurement campaign conducted from 01.06.2010 to 31.12.2013 in Freiburg im Breisgau, Germany, but the order of magnitude is considered to be typical. In order to validate the simplified uncertainty estimation method, a sensitivity analysis was carried out to evaluate the influences of calibration and drift of the spectroradiometer, high-angle-of-incidence conditions, the available wavelength range of the spectroradiometer and results obtained with different spectroradiometers. With the smaller wavelength range of 350–1050 nm, which is a typical range for various instruments used in many scientific publications, the calculated spectral impact was significantly smaller. The other influences were found to affect the result only within the estimated uncertainty limits. The uncertainty values presented here should be considered lower limits until they are backed up by further analysis.

Keywords: Spectral irradiance; Energy rating; Thin film photovoltaics; Spectroradiometer; Uncertainty

1. Introduction

The spectral distribution of incoming solar irradiance ('spectral irradiance') is known to vary depending on location, climate and weather situation, and to influence the performance of photovoltaic (PV) modules. Spectral

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irradiance was measured and investigated all around the world – from Japan over tropic regions, south Africa, southern and middle continental Europe, the UK and the US (Japan: (Ishii et al., 2012, 2011a,b, 2013b; Minemoto et al., 2007a,b, 2009; Nagae et al., 2006, 2009; Nakada et al., 2010), tropic regions: (Eltbaakh et al., 2013; Sirisamphanwong and Ketjoy, 2012), South Africa: (Okullo et al., 2011), Continental Europe: (Alonso-Abella et al., 2014; Behrendt et al., 2013, 2010; Cornaro and Andreotti, 2013; Dirnberger et al., 2015, 2011b; Driesse et al., 2012; Nofuentes et al., 2013; Perez-Lopez et al., 2007; Piliougine et al., 2013; Schweiger et al., 2012; Zinsser et al., 2011), UK: (Gottschalg et al., 2004, 2003), US: (King et al., 2002)).

The aforementioned publications focus on different spectrum-related topics, such as the determination of instantaneous, monthly or annual energetic impact on PV performance, the validation of approaches to simulate spectral irradiance, or the application of different indicators for relative spectral irradiance like average photon energy (APE) or spectral mismatch factor (MM).

When it comes to energy rating or yield predictions for PV modules and systems, the annual and monthly energetic impact of the varying spectral irradiance is of particular importance, as it can affect the effectively available irradiation (the integrated irradiance over a specific period of time) and thus the expected yield (kWh) by several percent (Alonso-Abella et al., 2014; Dirnberger et al., 2015; Ishii et al., 2013a). However, spectral irradiance data to determine this impact with respect to a specific PV technology and location is not readily available in sufficient temporal and spatial resolution (Huld et al., 2013). As a consequence, typical energy rating procedures or yield predictions do not consider the spectral impact at all, or just in form of fixed loss or gain factors applied to the total broadband irradiation (Huld et al., 2013; Thevenard and Pelland, 2013). The result of energy rating or yield prediction depends directly on this factor, and its uncertainty also propagates directly to the result. Despite this strong and direct influence, uncertainty of spectral impact has so far not been analyzed or discussed.

The work presented here is aimed at closing this gap by discussing contributions to uncertainty of the spectral impact determined by means of measured spectral irradiance and calculating MM, as done in (Dirnberger et al., 2015). The focus is on the measurement set-up and methodology from (Dirnberger et al., 2015), but the considerations are designed to be transferable to other cases. The article introduces a simplified uncertainty estimation for the annual spectral impact, which helps interpret spectral impact values, and will serve as a basis for future research.

2. Methodology

2.1. Experimental set up

The experimental set-up is the same as in (Dirnberger et al., 2015): Spectral irradiance was measured with two spectroradiometers, EKO MS-710 and MS-712, whose combined wavelength range is 335–1700 nm. The wavelength interval is 0.73 nm from 335 to 1100 nm (MS710), and 1.56 nm from 900 to 1700 nm (MS712); the spectral resolution (FWHM, full width at half maximum,) is 5 nm and 10 nm, respectively. The wavelength accuracy is better than 1.5 nm. The instruments are suitable for continuous outdoor exposure and capable of measuring the solar spectral irradiance in all typical ambient conditions. The integrating time is in a range of 100 ms (high irradiance conditions) to 5 s (low irradiance conditions).

The instruments are installed on the roof of Fraunhofer ISE, facing due south with a 30° tilt. The surrounding area is mostly urban, with the Black Forest directly to the east. Data was taken in the period from 01.06.2010 to 31.12.2013 in varying time increments (mostly every 1 min, partly in 30 s or 5 min increments), and resampled to 5-min averages. Due to recalibration in summer 2012 and other outage periods, data is lacking for several periods. The instruments were calibrated by the manufacturer at start of the measurement campaign, and recalibrated in summer 2012. Before, during and after the recalibration period in 2012 (exactly from 01.07.2012 to 28.11.2012), a spectroradiometer of the type MS-700 was provided by EKO instruments as alternative for spectral data acquisition during the calibration period. The MS-700 covered a wavelength range from 350 to 1050 nm, with a wavelength interval of 3.3 nm and a spectral resolution of 10 nm (FWHM). The MS-700 was installed directly next to the other two instruments. The data is used in Section 4 of the current article to compare the spectral impact determined with different instruments for a sample time frame.

Pyranometer measurements (5-min averages resampled from 10 s measurements) were used as indication of global broadband irradiance due to the limited spectral sensitivity of the spectroradiometer. The fact that wavelengths from 1700 to 4000 nm are not considered would lead to an offset towards lower irradiance levels. Furthermore, the absolute calibration of a pyranometer is subject to smaller uncertainty. Data for the whole period were taken from two pyranometers (both of them CMP11 Kipp & Zonen installed near the spectroradiometers, same tilt and orientation, one until 01.04.2011, the other afterwards).

2.2. Determination of annual energetic spectral impact

Before starting the discussion on uncertainty contributions, we briefly summarize the method for determination of annual spectral impact. More detailed explanations are given in (Dirnberger et al., 2015). The energetic impact of spectral irradiance is determined based on measurements of spectral irradiance, measurements of total broadband irradiance with a pyranometer and calculation of MM. The spectral impact is essentially the spectrally effective irradiance available to a PV device compared both to the total broadband irradiance measured by a pyranometer and the theoretical case of permanent spectral reference