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Solar spectral irradiance derived from satellite data: A tool to improve thin film PV performance estimations?

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Abstract

A detailed estimation of the expected yield from photovoltaic systems requires not only broadband solar irradiance but as well its spectral distribution. The SOLIS method to calculate spectrally resolved irradiance from satellite data is presented here. It is evaluated in two ways: using radiative transfer calculations and measurements of spectrally resolved global horizontal, global tilted and direct normal irradiance. The applicability of the SOLIS spectral irradiance to simulate the spectral effect for different photovoltaic materials is tested by calculating the spectral mismatch and the weighted irradiance at three sites using two different inputs: satellite-derived and measured irradiance. The results are compared to measurements of the short circuit current for various photovoltaic materials. Spectral measurements result in a spectral effect on the yield in the range of 2–6% for amorphous silicon and 1–4% for polycrystalline silicon which is reproduced by the SOLIS method. The differences between various sites under investigation due to weather conditions and inclination of the measurements are by tendency well described by the satellite-derived spectral irradiance with SOLIS. However, the results differ from the results using measurements of the short circuit current which are superimposed by other effects.

Keywords: Spectral effect; Solar irradiance; Satellite data

1. Introduction

Many applications in planning and monitoring of photovoltaic devices need an accurate estimate of the expected yield which mainly depends on the incident solar irradiance and temperature. Most models consider the broadband irradiance and temperature only, but also the spectral distribution of the irradiance affects the PV performance.

Every photovoltaic material uses (according to its band gap) a specific fraction of the solar spectrum to generate charge carriers. This can be described by the wavelength dependent quantum efficiency or the spectral response. For thin-film solar cells different semiconductor materials are used, some of them having a rather strong spectral sensitivity such as amorphous silicon (a-Si) (e.g. Nann and Emery, 1992). To have standardized module specifications the modules are characterized at standard test condition (STC: IEC, 2008) with includes a specific spectral distribution of irradiance (ASTM *AM*1.5 standard spectrum: ASTM, 2003). Fig. 1 shows measured spectra indicating large deviations from the standard spectrum as it varies with sun-earth geometry, cloudiness and atmospheric composition.

The information on the spectral distribution of irradiance incident on the PV module enables to improve performance estimations. Different approaches can be found to account for the effect of a varying spectral distribution on different photovoltaic materials. Measurements of module parameters are performed and correlated to solar eleva-

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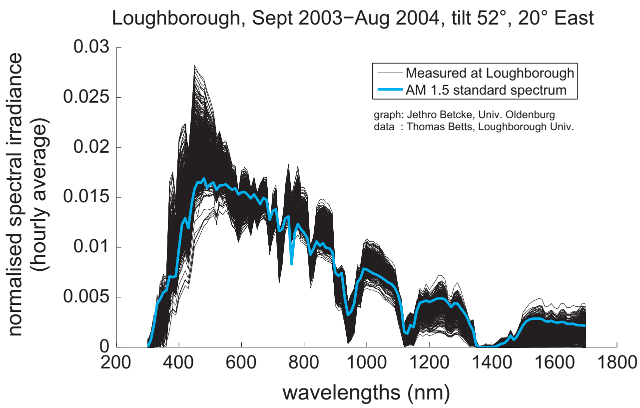

Fig. 1. Spectral irradiance normalized by broadband irradiance during 1 year measured at Loughborough University compared to the $AM1.5$ standard spectrum (ASTM).

tion by means of relative air mass (AM) and cloudiness (Huld et al., 2009) sometimes including measurements of spectrally resolved irradiance (Minemoto et al., 2009; Simon and Meyer, 2011; Kenny et al., 2004). Another approach is to measure spectrally resolved irradiance and theoretically derive the short circuit current or power (Houshyani Hassanzadeh et al., 2007; King et al., 1997; Perez-Lopez et al., 2007).

Depending on the installation different kinds of information are necessary. In most cases irradiance on a tilted plane is sufficient, for concentrating PV direct normal irradiance (DNI) is needed. As measurements of spectrally resolved irradiance are rare, satellite data offer the potential to derive long term data with high spatial and temporal resolution. To calculate the spectrally resolved direct normal and global horizontal irradiance the Heliosat method (Hammer et al., 2003) is used and combined with the SOLIS clear-sky model (Mueller et al., 2004).

The irradiance on a tilted plane has to be calculated from direct and diffuse horizontal irradiance by using an additional model. Different models exist for broadband irradiance (Harrison and Coombes, 1988). The Klucher model (Klucher, 1979) performs well compared to other even more recent models, as observed by for example Gueymard (2009). In this paper its applicability for spectrally resolved irradiance is analyzed.

Important steps to derive spectrally resolved irradiance are described in Section 2 of this paper. The effect on photovoltaic materials is described and parameters to characterize this effect are presented in Section 3. The presented method is evaluated by using radiative transfer and using ground measurements as reference (Section 4).

2. Spectral irradiance from satellite data

Different steps are applied to derive the spectrally resolved solar irradiance on a horizontal or tilted plane different as illustrated in Fig. 2. The cloud information is obtained from satellite data with the Heliosat method. The combination with SOLIS clear-sky results in spectrally resolved global, direct and diffuse irradiance for all sky situations on a horizontal plane (SOLIS method). An additional model (Klucher model) converts direct and diffuse horizontal irradiance provided by SOLIS to irradiance incident on a tilted plane.

2.1. Heliosat method

With the Heliosat method the information on cloudiness is determined from satellite data. Meteosat satellites offer 25 years data with a temporal resolution of 30 min (Meteosat First Generation) up to 15 min (Meteosat Second Generation – MSG) and a spatial resolution up to 1 km × 1 km (at sub-satellite point).

The Heliosat method uses the fact that a thick cloud layer is correlated with a low cloud transmissivity and a high reflectivity observed in space. This reflectivity is calculated from the broadband visible channel data. It is possible to derive a cloud index n which is transfered to the clear-sky index k^* as described in (Hammer et al., 2003). k^* represents a broadband measure of the transmissivity of clouds and is defined as the ratio of the actual global irradiance G to a simulated irradiance for a well defined clear-sky atmosphere G_{clear}. With k^*, the global irradiance G can be calculated by

$$G = k^* \cdot G_{clear}. \tag{1}$$

G_{clear} results from a clear-sky model such as SOLIS clear-sky. If the clear-sky irradiance is calculated considering a higher content of different atmospheric components than actually present k^* can get larger than 1. Additional reflection on broken clouds can also lead to higher global irradiance than the calculated clear-sky irradiance and therefore $k^* > 1$.

2.2. SOLIS clear-sky

The calculation of solar surface irradiance needs both the irradiance for cloudless skies G_{clear} and the information on cloudiness. Clear-sky models used at Oldenburg University with the Heliosat method (Hammer et al., 2003) were based on turbidity which integrates all atmospheric components and misses different spectral properties of these components. In contrast the SOLIS clear-sky model is based on the radiative transfer library libRadtran (Mayer and Kylling, 2005) and therefore is capable of accounting for the atmospheric composition, namingly the highly variable atmospheric constituents aerosols and water vapor. SOLIS clear-sky calculates spectrally resolved global and direct irradiance depending on geometrical and atmospherical influences using the modified-Lambert–Beer parameterization to account for diurnal variations of the irradiance with reduced computation time (Mueller et al., 2004). Results of SOLIS clear-sky are $DNI_{clear}(\lambda)$ and $G_{clear}(\lambda)$ with 32 spectral bands