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Proposal and evaluation of subordinate standard solar irradiance spectra for applications in solar energy systems

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ABSTRACT

Reference solar irradiance spectra are needed to specify key parameters of solar technologies such as photovoltaic cell efficiency, in a comparable way. The IEC 60904-3 and ASTM G173 standards present such spectra for Direct Normal Irradiance (DNI) and Global Tilted Irradiance (GTI) on a 37° tilted sun-facing surface for one set of clear-sky conditions with an air mass of 1.5 and low aerosol content. The IEC/G173 standard spectra are the widely accepted references for these purposes. Hence, the authors support the future replacement of the outdated ISO 9845 spectra with the IEC spectra within the ongoing update of this ISO standard.

The use of a single reference spectrum per component of irradiance is important for clarity when comparing and rating solar devices such as PV cells. However, at some locations the average spectra can differ strongly from those defined in the IEC/G173 standards due to widely different atmospheric conditions and collector tilt angles. Therefore, additional subordinate standard spectra for other atmospheric conditions and tilt angles are of interest for a rough comparison of product performance under representative field conditions, in addition to using the main standard spectrum for product certification under standard test conditions. This simplifies the product selection for solar power systems when a fully-detailed performance analysis is not feasible (e.g. small installations). Also, the effort for a detailed yield analyses can be reduced by decreasing the number of initial product options.

After appropriate testing, this contribution suggests a number of additional spectra related to eight sets of atmospheric conditions and tilt angles that are currently considered within ASTM and ISO working groups. The additional spectra, called subordinate standard spectra, are motivated by significant spectral mismatches compared to the IEC/G173 spectra (up to 6.5%, for PV at 37° tilt and 10–15% for CPV). These mismatches correspond to potential accuracy improvements for a quick estimation of the average efficiency by applying the appropriate subordinate standard spectrum instead of the IEC/G173 spectra.

The applicability of these spectra for PV performance analyses is confirmed at five test sites, for which subordinate spectra could be intuitively selected based on the average atmospheric aerosol optical depth (AOD) and precipitable water vapor at those locations.

The development of subordinate standard spectra for DNI and concentrating solar power (CSP) and concentrating PV (CPV) is also considered. However, it is found that many more sets of atmospheric conditions would be required to allow the intuitive selection of DNI spectra for the five test sites, due in particular to the stronger effect of AOD on DNI compared to GTI.

The matrix of subordinate GTI spectra described in this paper are recommended to appear as an option in the

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annex of future standards, in addition to the obligatory use of the main spectrum from the ASTM G173 and IEC 60904 standards.

1. Introduction

Reference solar irradiance spectra are needed for specification and comparison of solar technologies such as the efficiency of photovoltaic (PV) cells. Other examples for spectrally-dependent parameters are the reflectance, absorptance, or transmittance of optical elements such as glass covers, absorbers, or optical concentrators. Standard direct and global irradiance spectra for one specific set of atmospheric conditions were first standardized by the American Society of Testing and Materials (ASTM) in the 1980s (ASTM E891, E892), then by the International Organization for Standardization (ISO) (ISO, 1992) and other standardization bodies such as the International Electrotechnical Commission (IEC) (IEC, 2016). The latest generation of these reference spectra is based on developments from the early 2000s (Gueymard et al., 2002). ASTM G173 was first adopted in 2003, and is still current (ASTM, 2012). G173 presents Direct Normal Irradiance (DNI) and Global Tilted Irradiance (GTI) on a 37° sun-facing tilted surface for air mass 1.5 (AM1.5), clear-sky conditions, and low aerosol optical depth (AOD) of 0.084 at 500 nm. The AM1.5 specification was essentially motivated by applications to concentrating PV (CPV) applications, as discussed in (Emery et al., 2002; Bird et al., 1983; Gonzalez and Ross, 1980). This specification was found to be somewhat less relevant to PV applications, however (Gonzalez and Ross, 1980). The GTI and DNI spectra in IEC 60904 (IEC, 2016) are based on, and nearly identical to, the G173 spectra. A constant multiplication factor of 0.99708 is used to convert the GTI values of G173 into the IEC 60904 values to achieve broadband irradiances exactly corresponding to standard conditions (1000 W/m^2 GTI). The spectral distribution of GTI and DNI from (IEC, 2016) is otherwise identical to G173 except for the number of reported decimal places in a few cases. The IEC 60904 standard is used as a starting point for this work because (i) it is the official reference to report PV standard conditions; (ii) it is the most recent one; and (iii) it integrates the core knowledge from previous ISO and ASTM standards (Gueymard et al., 2002).

One single reference spectrum for GTI (or DNI) is used when products such as PV (or CPV) cells or modules have to be rated against a single universal reference. To that end, (IEC, 2016) provides DNI and GTI reference spectra for the aforementioned atmospheric conditions. In parallel, (ISO, 1992) contains different spectra (identical to ASTM E891 and E892), but this standard is outdated and currently being updated. The authors support the future replacement of these ISO 9845 spectra with the current IEC spectra. The special role and importance of these current spectra are not questioned here. Hence, the IEC DNI and GTI spectra should continue to be maintained and recognized for their international value. However, they might not be representative of actual or "typical" conditions at many locations around the world. To address this situation, additional spectra are developed here for future standards.

The present contribution focuses on the development of "subordinate standard GTI spectra" for regional localization purposes, which should be made available in future standards. To avoid confusion, the new additional spectra are here referred to as *subordinate* standard spectra, in order to emphasize their supplementary character and their secondary role compared to the existing IEC and G173 spectra. Such subordinate spectra are intended to appear only in the annex of the forthcoming ISO standard to underline the special importance of the main standard spectra. The main potential application of subordinate spectra is to facilitate a quick and simple analysis for selecting products adapted to regional markets. The usage of proposed subordinate spectra for small-scale solar energy installations or during the first steps of project development for bigger installations is meant to improve the product selection and contribute to cost reductions in solar energy utilization. Although a wide range of atmospheric conditions could be covered by such additional spectra in principle, their number should be limited to keep product specifications clear and comparable, and avoid confusion or misuse.

This work presents the development of subordinate standard spectra related to various sets of atmospheric conditions and tilt angles that are currently under discussion within the ASTM and ISO working groups. This study is based on an analysis of spectral mismatches for several fixed tilted PV cells, tracking CPV cells, and CSP materials. The paper is structured as follows: First, the investigated solar devices and the definition of spectral mismatch are presented in Section 2. Section 3 introduces the tested additional spectra with regard to the atmospheric conditions used for their calculation. Thereafter, Section 4 compares the additional spectra among each other directly and in terms of their effect on the responsivity of various solar devices. Additionally, the influence of the tilt angle on that responsivity is examined, and examples for practical application of these spectra are given. In Section 5 the intuitive selection of a suitable additional spectrum is tested for exemplary sites with regard to the spectrum's ability to improve the estimation accuracy of solar device efficiency. Finally, in Section 6 the findings are summarized and recommendations for subordinate standard spectra in future standards are given.

2. Investigated solar devices and spectral mismatch

Fig. 1 displays the spectral responsivity R_λ of exemplary PV cells, normalized to their respective maximum. Since the spectral responsivity differs considerably among cell types, the influence of the

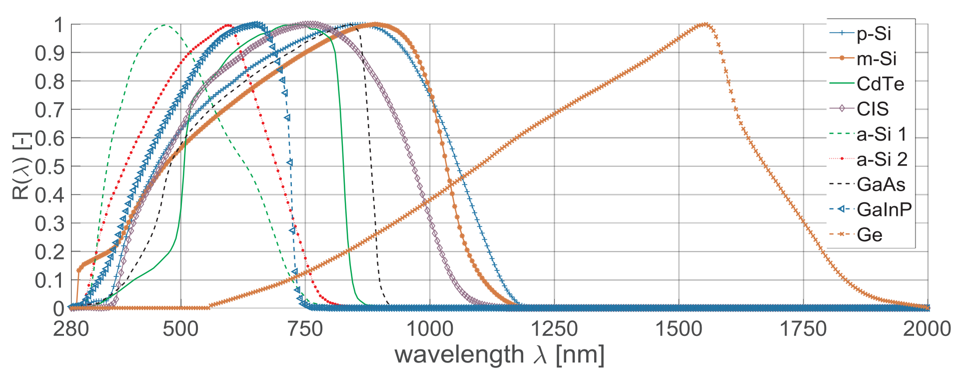

Fig. 1. Normalized spectral responsivity for exemplary PV cells (Winter et al., 2009).