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Cloud and albedo enhancement impacts on solar irradiance using high-frequency measurements from thermopile and photodiode radiometers. Part 2: Performance of separation and transposition models for global tilted irradiance

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ABSTRACT

Based on high-accuracy irradiance measurements at a high-elevation station frequently affected by snow cover, this experimental study evaluates the interannual variability in high global tilted irradiance (>1 sun) incident on either latitude-tilt (40°) or vertical-tilt (90°) radiometers at 1-min resolution. Using a 10-year time series, this variability is found substantial, particularly for the 90° tilt. The performance of five separation and seven transposition models is also analyzed in general, and most specifically under cloud and/or albedo enhancement events. The separation models' performance degrades rapidly for clearness indices larger than 0.8, to the point that three models tend to predict zero direct normal irradiance when it is actually high. Only one model (Engerer) can predict acceptable results, even though negatively biased under such conditions. All transposition models are also impacted by enhancement events. This is most particularly the case for one of them (Perez), which tends to predict an extremely low sky-diffuse component during those events, and even negative values in the case of the 90° tilt. An analysis of the models' performance as a function of the clearness index reveals that most models are affected by a rapid degradation of performance when this index is larger than 0.8. For the 40° tilt and on average over 10 years, the bias of the CDRS model is found reasonably low and stable even when the index approaches its maximum value. The maximum recorded value of GTI is ≈2000 W m^{-2} (2 suns) for the 40° tilt, using 1-s data. For the 90° tilt, no model has a low and stable bias under all possible conditions, but the CDRS model still performs reasonably well under high clearness index conditions. All these findings confirm the fact that separation or transposition models that were empirically developed based on hourly irradiance data do not necessarily respond correctly to transient enhancement situations.

1. Introduction

The need for detailed solar resource assessments and photovoltaic (PV) system output simulations at ever-increasing spatial and temporal resolutions is presenting challenges for the existing radiation models in common use today for plane-of-array (POA) calculations. There are typically two categories of such models, each one performing an essential task in the overall process: (i) *separation* of the direct and diffuse components from global horizontal irradiance (GHI); and (ii) *transposition* of these components from horizontal to the tilted POA geometry to ultimately obtain the global tilted irradiance (GTI). Most, if not all, "industry-standard" models in these two categories are empirical and were designed decades ago based on hourly radiation data. Current measurements, however, are now typically done at 1-min resolution or better.

Part 1 of this study highlighted the relatively frequent occurrence of transient cloud enhancement (CE) effects, potentially augmented by albedo enhancement (AE) effects, when considering measurements of GHI at a time step of 1 min. For instance, at the Golden, Colorado site under scrutiny, GHI was found >1 sun (i.e., 1 kW m^{-2}) 3.8% (5.7%) of the time, and 0.6% (1.1%) larger than its extraterrestrial counterpart, when using thermopile (photodiode) radiometers, respectively, on average over 10 years and at 1-min resolution. During the same period, an overall maximum GHI of 1.546 kW m^{-2} was recorded with a thermopile pyranometer, and 1.634 kW m^{-2} with a photodiode sensor, indicating that the type

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of sensor is an important consideration when reporting CE effects. Similarly, the measurement time step also appears to matter, since even larger maximum values (up to 1.9 suns) were obtained at 1-s resolution. Part 1 described three types of circumstances potentially leading to CE events, with or without contribution from simultaneous AE events. In this Part 2, the main focus is on high-GTI cases, irrespective of the circumstances causing them, but with additional scrutiny on the impact of high-albedo conditions.

Some important questions remain to be addressed in detail, most particularly: Do transient effects impact GTI more than GHI? How large GTI can be under very short transient periods? How do separation and transposition models of the literature, which were designed for coarser hourly simulations, behave at higher frequency? What kind of instrumentation is necessary to evaluate the performance of such models under rapidly changing conditions? What is the ideal measurement frequency for these measurements? And how do these enhancement events impact the power output of PV systems and their inverters?

This study's Part 2 intends to address these questions, except the last one (which is of a very different nature), and in so doing provide more background knowledge about enhancement effects in the context of PV applications. Like in Part 1, the main focus is on the description of high-irradiance events, since only these can negatively impact the design, safety and reliability of PV systems (Chen et al., 2013; Luoma et al., 2012). The possible impacts (positive or negative) on overall PV performance are still unclear, due to conflicting effects (Burger and Rüther, 2006; Luoma et al., 2012; Öchsner et al., 2013; Zehner et al., 2011). The reader is referred to Part 1 for a literature review about the connection between enhancement events and their potential effects on PV systems.

Recent contributions (Cucumo et al., 2007; Gueymard, 2009; Lave et al., 2015; Yang et al., 2013) have started to investigate how the different possible combinations of specific separation and transposition models affected the accuracy of the modeled GTI. Interestingly, a general finding is that the accuracy of the first step (component separation) is what conditions in large part the uncertainty in the GTI predictions (component transposition). As a consequence, the transposition model with the highest intrinsic performance might not provide the best GTI accuracy, due to the potentially incorrect balance between the estimated direct and diffuse components of GHI resulting from the first step. Since compensations of errors might be highly location specific, it is argued here that the best avenue, with the highest chances for universal validity, is to separately look for the most accurate models in each category. This means that the first step (component separation) must provide the direct horizontal irradiance (DHI)—or, alternatively, the direct normal irradiance (DNI)—and the diffuse horizontal irradiance (DIF) with minimal error.

From that perspective, a recent study (Gueymard and Ruiz-Arias, 2016) has shown that hourly separation models do not always produce correct results when using input data of GHI at 1-min resolution, most particularly under transient cloud situations or over highly reflective surfaces. What has just been mentioned justifies further investigation into the effects of rapid fluctuations in GHI on the modeled GTI due to CE and/or AE episodes, which can typically last from a fraction of a second to several minutes. The present study intends to bring a new perspective and a quantitative assessment on the impact of CE and/or AE effects on the modeled GTI. So far, most of the literature has focused on the CE effects on GHI, as discussed in Part 1. However, the ramping effects on inverters and PV power output are actually dependent on GTI rather than GHI, since the vast majority of solar panels are mounted at a tilt rather than horizontally. The horizontal-to-tilted solar irradiance transposition has been shown to directly impact the modeling of PV array performance (Polo et al., 2016; Roberts et al., 2017; Yoshida et al., 2013), but these studies did not consider enhancement effects or high-frequency data, which justifies additional scrutiny.

In addition to CE effects, GTI can also be impacted by albedo enhancement (AE) effects caused by larger-than-usual ground albedo (e.g., over snow-covered ground) and/or large deviations from the conventionally assumed isotropy of ground reflection. A large *regional* surface albedo increases DIF and GHI through atmospheric backscattering, as discussed in Part 1. A separate phenomenon is the increase in GTI caused by high *local* albedo facing solar collectors and by the associated local non-Lambertian reflection processes; see, e.g., (Andrews and Pearce, 2013; Gueymard, 1987, 2009; Ineichen, 1990; Kierkus and Colbrone, 1989; Skartveit et al., 1998; Temps and Coulson, 1977; Weiser et al., 2016; Yoon et al., 2014). As discussed in Part 1, difficulties arise because the local and regional albedos can be widely different at any moment. So far, the literature does not seem to have considered the combination of CE and AE effects on GTI, which justifies the present study.

The discussion above demonstrates the importance of quantifying how CE, regional-AE and/or local-AE events impact the separation and transposition models that are customarily used to ultimately convert GHI into GTI. To that end, this study critically evaluates the high-frequency performance of a variety of both types of model under various surface conditions, as well as highly variable cloud conditions. So far the literature has reported a record GTI of 1.6 suns in Norway (Yordanov et al., 2015). In California, several 1-s periods with GTI > 1.5 suns have been reported by (Luoma et al., 2012). In contrast, Part 1 of this study has uncovered a record 1-s GHI measurement of ≈1.9 suns, and frequent 1-min GHI measurements above 1.5 suns. Since GTI is generally larger than GHI, this Part 2 investigates the corresponding peaks in GTI, in an effort to estimate the frequency of very high GTI values that can impact PV systems, and to evaluate whether routine GHI-to-GTI calculations can provide the correct magnitude of extreme GTI events.

2. Separation models

A recent study (Gueymard and Ruiz-Arias, 2016) evaluated the performance of 140 separation models under various climatic conditions. Using irradiance data at 54 research-class stations, two important findings of that study were that (i) some separation models that had been developed from hourly data showed significant issues when 1-min input data were used instead; and (ii) most of these issues were triggered by CE and/or AE effects. This justifies the more specific analysis undertaken here. However, to maintain it within reasonable limits, only five separation models are considered in what follows. For clarity, reference to these models utilizes the specific notation (SMALL CAPS) that was introduced in (Gueymard and Ruiz-Arias, 2016) and later also adopted in (Yang, 2016) for the case of transposition models. The popular ERBS, MAXWELL, PEREZ1 and PEREZ2 models (Erbs et al., 1982; Maxwell, 1987; Perez et al., 1992, 2002) were developed from hourly data, whereas the ENGERER model (Engerer, 2015) was developed from 1-min data. The latter demonstrated the best performance results overall in the aforementioned study (Gueymard and Ruiz-Arias, 2016). ERBS and ENGERER provide an estimate of the diffuse fraction, $K = \mathrm{DIF}/\mathrm{GHI}$, from which DHI can be simply derived using the closure equation, $\mathrm{DHI} = \mathrm{GHI}–\mathrm{DIF} = \mathrm{GHI}\,(1 - K)$. In contrast, MAXWELL, PEREZ1 and PEREZ2 evaluate the direct transmittance, $K_n = \mathrm{DNI}/\mathrm{ETN}$, where ETN is the extraterrestrial irradiance at normal incidence, and then finally $\mathrm{DHI} = \mathrm{DNI} \cos Z$ and $\mathrm{DIF} = \mathrm{GHI} - \mathrm{DHI}$, where Z is the sun's zenith angle. Both ENGERER and PEREZ2 require estimates of the clear-sky irradiances, which are simply obtained here through the Perez-Ineichen clear-sky radiation model (Perez et al., 2002), per the

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