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Review

Extensive worldwide validation and climate sensitivity analysis of direct irradiance predictions from 1-min global irradiance

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Abstract

A comprehensive evaluation study of the performance of 140 separation models selected from the literature to predict direct normal irradiance (DNI) from global horizontal irradiance (GHI) is presented here. The assessment is conducted using high-quality 1-min data of GHI and DNI at 54 research-class stations from 7 continents. The observational dataset provides (after *a posteriori* quality control) more than 25 million valid data points, thereby representing an unprecedented level of effort. The stations are grouped into 4 distinct climate zones: arid, temperate, tropical and high-albedo. To evaluate the performance of each model at each site, three summary statistics are calculated. Additionally, with the emphasis on selecting models that perform consistently well under the general conditions of each climate zone, the robustness of each model is evaluated using a few consistency criteria.

It is found that, for all models, the errors are exacerbated by cloud enhancement and high-albedo induced effects. A higher number of predictors used by a model appears to improve its performance, but not in a consistent way, since there are many exceptions. These are attributed to possible excessive model localization and/or overfitting. In general, models that consider both a variability predictor and an estimate of coincident clear-sky irradiance tend to perform better. No model performs consistently well over the high-albedo zone, even those rare ones that do consider ground albedo as a predictor. Over the arid, temperate and tropical zones, two models consistently deliver the best predictions. One of them is recommended as a "quasi-universal" model for general use for 1-min DNI prediction wherever and whenever low- to moderate-albedo conditions prevail.

Keywords: Direct–diffuse separation; DNI; Irradiance variability; Cloud enhancement; Validation; Albedo

Contents

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1. Introduction

The correct design and energy performance simulation of solar power systems, as well as various different applications in other scientific fields, require precise solar radiation data in terms of both direct normal irradiance (DNI) and diffuse horizontal irradiance (DIF). (The acronym DIF is purposefully used in lieu of DHI in this context to avoid possible confusion with the latter's alternative meaning of direct horizontal irradiance.) A ubiquitous type of calculation in solar applications consists in deriving the global tilted irradiance (GTI) on the plane of array of flat-plate solar collectors, which involves the separate modeling of the direct and diffuse tilted components. The DNI/DIF separation process in such methods is typically the major source of error in GTI (Gueymard, 2009). At locations with significant solar resource, DNI is normally the dominant component, hence the importance of its correct determination. Moreover, DNI is essential for concentrating solar power (CSP) or concentrating PV (CPV) systems, since this is the only solar radiation component that they can utilize. One difficulty is that DNI observations are relatively rare, particularly compared to those of global horizontal irradiance (GHI). Hence, in most cases, DNI is derived from measured or modeled GHI by performing its "separation" or "decomposition" into its two components, DNI and DIF. This is also done systematically, for instance, to produce time series of DNI when GHI is derived from satellite imagery with the common "cloud index" method (Perez et al., 2002; Polo et al., 2014). The separation process contributes very importantly to the overall uncertainty in such databases (Cebecauer et al., 2011).

Publications proposing a statistical separation equation based on observational data have proliferated since the very first, and seminal, study from (Liu and Jordan, 1960), hereafter LJ60, now more than 55 years old. The usual lack of science and extreme localization in this class of models has pushed the adoption of strict guidelines by at least one archival journal, aimed at restricting their publication (Gueymard et al., 2009; Kasten and Duffie, 1993). Still, such models continue to be developed and used, however with a lack of evidence about which one can provide the best possible results at any specific location where no DNI or DIF measurement exists. One important difficulty here is that the current separation models are empirically derived from site-specific measurements, and cannot be attributed a precise uncertainty without extensive evaluation. Validation studies do exist (e.g., Battles et al., 2000; Bertrand et al., 2015; De Miguel et al., 2001; Dervishi and Mahdavi, 2012; Engerer, 2015; Ineichen, 2008; Jacovides et al., 2010; Karatasou et al., 2003; Kuo et al., 2014; Perez et al., 1990b; Ruiz-Arias et al., 2010; Skartveit et al., 1998; Spencer, 1982; Tapakis et al., 2015; Torres et al., 2010; Vick et al., 2012; Yao et al., 2013), but are inherently limited in scope to a small number of models and test stations. Moreover, most of them aim at validating DIF rather than DNI. The validation of DNI predicted from a larger number of models has been considered in recent studies from the present authors (Gueymard, 2010; Gueymard and Ruiz-Arias, 2014), but the number of stations was still limited in number and/or climatic conditions, thus making generalization of the results difficult.

From another perspective, the temporal resolution of solar radiation data has considerably improved since the early days of solar energy development, represented here by the LJ60 study. During the last few decades, the reporting of solar radiation data from modern radiometric stations has moved from a hourly time step to much shorter steps, generally 1- to 10-min intervals, and sometimes even shorter. In parallel, the proper energy simulation of CSP projects requires solar radiation data at time steps shorter than the customary hourly interval. This is because of the non-linear and transient effects that substantially affect