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# Assessment of uncertainty in the numerical simulation of solar irradiance over inclined PV panels: New algorithms using measurements and modeling tools

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ABSTRACT

Development of accurate transposition models to simulate plane-of-array (POA) irradiance from horizontal measurements or simulations is a complex process mainly because of the anisotropic distribution of diffuse solar radiation in the atmosphere. The limited availability of reliable POA measurements at large temporal and spatial scales leads to difficulties in the comprehensive evaluation of transposition models. This paper proposes new algorithms to assess the uncertainty of transposition models using both surface-based observations and modeling tools. We reviewed the analytical derivation of POA irradiance and the approximation of isotropic diffuse radiation that simplifies the computation. Two transposition models are evaluated against the computation by the rigorous analytical solution. We proposed a new algorithm to evaluate transposition models using the clear-sky measurements at the National Renewable Energy Laboratory's (NREL's) Solar Radiation Research Laboratory (SRRL) and a radiative transfer model that integrates diffuse radiances of various sky-viewing angles. We found that the radiative transfer model and a transposition model based on empirical regressions are superior to the isotropic models when compared to measurements. We further compared the radiative transfer model to the transposition models under an extensive range of idealized conditions. Our results suggest that the empirical transposition model has slightly higher cloudy-sky POA irradiance than the radiative transfer model, but performs better than the isotropic models under clear-sky conditions. Significantly smaller POA irradiances computed by the transposition models are observed when the photovoltaics (PV) panel deviates from the azimuthal direction of the sun. The new algorithms developed in the current study have opened the door to a more comprehensive evaluation of transposition models for various atmospheric conditions and solar and PV orientations.

## 1. Introduction

Solar radiation is routinely measured or computed on horizontal surfaces (Sengupta et al., submitted for publication, 2014; Xie et al., 2016) while most photovoltaic (PV) applications require irradiance on inclined surfaces. Therefore, transposition models are used to convert global horizontal irradiance (GHI) and direct normal irradiance (DNI) to plane-of-array (POA) irradiance. The major uncertainty in transposition models results from the complexity of integrating diffuse radiation received at the POA that has been previously scattered by air molecules, aerosols and clouds in the atmosphere and partially reflected by the land surface.

The isotropic approximation of diffuse radiance can substantially simplify the transposition models though the spatial distribution of diffuse radiance is usually anisotropic and highly dependent on specific atmospheric conditions (Xie et al., 2012). A transposition model using the isotropic approximation (hereafter referred to as the isotropic model) was reported by Liu and Jordan (1963) (hereafter referred to as LJ1963). During the recent decades, this model has become one of the most popular transposition models because it has a simple relationship to diffuse horizontal irradiance (DHI) even though it exhibits higher bias compared to models that account for both the isotropic and anisotropic components of diffuse radiation (Jakhrani et al., 2012; Loutzenhiser et al., 2007; Noorian et al., 2008). Badescu (2002) derived a solution for the isotropic model based on a 2-D geometry and found that it has the same expression as LJ1963. He further derived the solution based on a 3-D geometry (hereafter referred to as BA2002) and evaluated it using LJ1963 and a model developed by Brunger and Hooper (1993). The solution of BA2002 showed better accuracy compared to LJ1963 when the model of (Brunger and Hooper, 1993) was

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used as ground truth (Badescu, 2002).

Many other transposition models simulate the contribution of diffuse sky radiation using empirical equations (hereafter referred to as empirical models) determined from surface observations of DHI and POA irradiance (Perez et al., 1990; Reindl et al., 1990). Compared to isotropic models, these empirical models have better representations of diffuse radiation in the presence of aerosols and thin clouds, especially around forward directions (Dave, 1977; Steven, 1977; Xie, 2010). However, the accuracy of empirical models might vary with solar and PV tilt angles as well as with season and location. The rapid variation of meteorological or land surface conditions—e.g., a sudden snowfall—-might lead to non-ignorable biases in empirical models that rely on long-term observations.

A number of studies have utilized surface observations to assess the performance of transposition models (Gueymard, 1987; Gueymard and Ruiz-Arias, 2016; Jakhrani et al., 2012; Kamali et al., 2006; Khalili and Shaffie, 2013; Lave et al., 2015; Loutzenhiser et al., 2007; Noorian et al., 2008; Pandey and Katiyar, 2009). A significant uncertainty of those studies is that the limited availability of surface observations restricts the analysis with limited temporal and spatial domains. Thus, there exists a need to analyze the transposition models in a broader context and systematically understand their reliability under varying meteorological conditions. To achieve this goal, we propose new algorithms to evaluate transposition models using both measurements and modeling tools. We first review the analytical derivation of POA irradiance and its numerical solution based on transposition models. The surface-based observations taken at the National Renewable Energy Laboratory's (NREL's) Solar Radiation Research Laboratory (SRRL) are used to compare with simulations from the isotropic models, an empirical model, and a new radiative transfer model, Fast All-sky Radiation Model for Solar applications with Narrowband Irradiances on Tilted surfaces (FARMS-NIT). FARMS-NIT computes POA irradiance under extensive atmospheric conditions and can be used to analyze the transposition models and explore the physical sources of their uncertainties.

## 2. Computation of solar irradiance over inclined PV panels

### 2.1. Solutions of POA irradiance

Following previous studies (Gueymard, 1987; Jakhrani et al., 2012; Loutzenhiser et al., 2007; Noorian et al., 2008), POA irradiance over a monofacial PV panel can be given by

$$POAI = POAI_d + POAI_{u,sky} + POAI_{u,ground} \tag{1}$$

where $POAI_d$, $POAI_{u,sky}$, and $POAI_{u,ground}$ are the POA irradiances associated with direct irradiance, diffuse irradiance from sky, and diffuse irradiance from ground reflection, respectively. $POAI_d$ can be computed by

$$POAI_d = DNI\cos\theta' \tag{2}$$

where DNI represents direct normal irradiance, and $\theta'$ is the angle between incident solar beam and the normal direction of the inclined PV panel. The geometry and derivation of $\theta'$ can be found in Appendix A.

The diffuse POA irradiance from the sky can be given by the integration of radiances along the perpendicular direction to the PV panel:

$$POAI_{u,sky} = \int_0^{2\pi}\int_0^{\Theta(\beta,\phi)} I\cos\theta'\sin\theta d\theta d\phi \tag{3a}$$

where I is the diffuse radiance from the sky, β is the tilt angle of the PV panel, ϕ is the azimuth angle, and Θ(β, ϕ) denotes the upper limit of θ for each ϕ. Because the contribution of radiances to POA irradiance must be positive, the integration in Eq. (3a) satisfies:

$$\cos\theta' = \cos\beta\cos\theta + \sin\beta\sin\theta\cos\phi \geqslant 0 \tag{3b}$$

Thus, Θ(β, ϕ) can be solved from Eq. (3b) when $\cos\theta' = 0$:

$$\Theta(\beta,\phi) = \begin{cases} \frac{\pi}{2} & \text{when } -\frac{\pi}{2} \leqslant \phi \leqslant \frac{\pi}{2} \\ \frac{\pi}{2} - \tan^{-1}(-\tan\beta\cos\phi) & \text{when } \frac{\pi}{2} \leqslant \phi \leqslant \frac{3\pi}{2} \end{cases} \tag{3c}$$

The diffuse POA irradiance caused by the reflection of the ground can be given by the integration of reflected radiances along the perpendicular direction to the land surface:

$$POAI_{u,ground} = \int_0^{2\pi}\int_0^{\frac{\pi}{2}-\Theta(\beta,\phi)} I_r\cos\theta'\sin\theta d\theta d\phi \tag{4}$$

where $I_r$ is the reflected radiance by the land surface.

### 2.2. Isotropic models

LJ1963 and BA2002 as well as other isotropic models (Koronakis, 1986; Tian et al., 2001) have been widely used in studies of solar energy (Gueymard, 1987; Jakhrani et al., 2012; Loutzenhiser et al., 2007; Noorian et al., 2008; Threlkeld, 1962).

When diffuse radiation from the sky and ground are assumed to be perfectly isotropic, Eqs. (3a) and (4) can reduce to

$$POAI_{u,sky} = \frac{1+\cos\beta}{2}DHI \tag{5a}$$

and

$$POAI_{u,ground} = \frac{1-\cos\beta}{2}GHI\sigma \tag{5b}$$

where σ represents the land surface albedo. Details on deriving the analytical solution of the isotropic approximation can be found in Appendices B and C.

To validate the analytical solutions of LJ1963 and BA2002, we set up a computer model to numerically compute $POAI_{u,sky}$ and $POAI_{u,ground}$ using Eqs. (3) and (4). To represent the isotropic diffuse radiation, cos θ is set as $0.0, 0.001, 0.002, \ldots, 1.0$; and ϕ is assumed as $0.0°, 0.05°, 0.1°, \ldots, 180.0°$. Then $POAI_{u,sky}/DHI$ and $POAI_{u,ground}/(GHI\sigma)$ can be numerically computed by Eqs. (3), (4), and (B1) as functions of β. Fig. 1 compares $POAI_{u,sky}/DHI$ and $POAI_{u,ground}/(GHI\sigma)$ simulated by LJ1963, BA2002, and the computer model. As shown, the simulations from the computer model match the analytical solutions of LJ1963 denoted by Eq. (5). Compared to the computer model, BA2002 underestimates diffuse POA irradiance from the sky with an uncertainty up to 15% (see Fig. 1a). In addition, BA2002 overestimates diffuse POA irradiance reflected by land surface as demonstrated by Fig. 1b. The uncertainty of $POAI_{u,sky}$ from BA2002 can be partially eliminated by $POAI_{u,ground}$ depending on the tilt angle and land surface albedo. More details on the comparison between LJ1963 and BA2002 can be found in Appendix B.

### 2.3. Radiative transfer model

Radiative transfer models numerically compute the transmission of monochromatic or broadband radiation through the atmosphere, which involves interactions with atmospheric constituents and land surface. Unlike transposition models that parametrically compute POA irradiance from horizontal irradiance, radiative transfer models compute diffuse radiances with necessary approximations for possible orientations in the atmosphere, leading to physics-based solutions of POA irradiance from Eqs. (3) and (4) (Hestenes et al., 2007; Stamnes et al., 1988). Despite the analytically more rigorous solutions, most radiative transfer models are 1-dimensional models that do not account for cloud overlap effects and 3D cloud effects, which affects accurate computation of diffuse solar radiation. Compared to the isotropic models, they are more time-consuming because of the complexity in solving the radiative transfer equation and efforts to couple land surface with the atmosphere (Chandrasekhar, 1950).