# Performance Analysis of Transposition Models Simulating Solar Radiation on Inclined Surfaces

## Preprint

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# Performance Analysis of Transposition Models Simulating Solar Radiation on Inclined Surfaces

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ABSTRACT: Transposition models are widely used in the solar energy industry to simulate solar radiation on inclined photovoltaic (PV) panels. These transposition models have been developed using various assumptions about the distribution of the diffuse radiation, and most of the parameterizations in these models have been developed using hourly measurements. Numerous studies have compared the performance of transposition models but this paper aims to understand the quantitative uncertainty in the state-of-the-art transposition models and the sources leading to the uncertainty using high-resolution ground measurements in the plane-of-array. Our results suggest that the aerosol optical depth (AOD) can affect the accuracy of isotropic models. The choice of empirical coefficients and the use of decomposition models can both result in uncertainty in the output from the transposition models. It is expected that the results of this study will ultimately lead to improvement of the parameterizations as well as the development of improved physical models.

Keywords: transposition model, solar radiation

## 1. INTRODUCTION

Significant growth in the number and size of solar energy projects has increased the demands for accurately measuring and modeling solar radiation. Although solar radiation data from surface measurements[1] or satellite retrievals[2] are routinely available on horizontal surfaces, photovoltaic (PV) panels are generally placed at a tilt to receive more solar radiation than horizontal surfaces. Compared to global horizontal irradiance (GHI), the partition of total solar radiation in the normal direction of inclined surfaces or plane-of-array (POA) irradiance is more closely correlated with PV system performance. As POA solar radiation measurements are generally not available and it is difficult to store POA irradiances for variable PV tilt angles, it is normally easier to compute the POA values from GHI and direct normal irradiance (DNI) using a transposition model [3-7].

Almost all transposition models compute POA irradiance from three contribution sources: direct sky radiation, diffuse sky radiation, and reflected radiation by land surface. Among the current transposition models, the contribution from diffuse sky radiation is simulated by either following empirical equations correlating it to diffuse horizontal irradiance (DHI) (hereafter referred to as the empirical model)[3, 5] or assuming the diffuse radiances are isotropic over the sky dome (hereafter referred to as the isotropic model)[6, 7]. Compared to isotropic models, empirical models account for the strong forward scattering by clouds or aerosols [8, 9]; thus, they are likely to better simulate POA irradiance on inclined PV systems. However, empirical models are developed to minimize model uncertainty from long-term observations at specific locations. The variation in time and geographic position may lead to diverse atmospheric and land surface conditions and significantly affect the accuracy of the empirical models.

Thus, accurate atmospheric and land surface information in high temporal and spatial resolutions can help reduce the uncertainties in the existing isotropic and empirical models. A reliable physics-based model that benefits from the rapid development of remote sensing technologies, e.g. remarkably improved aerosol and cloud products from the future Geostationary Operational Environmental Satellite R (GOES-R), should provide more precise estimation of PV system performance.

To understand the improvement in the future physics-based model, it is first necessary to quantitatively estimate the uncertainties in the state-of-the-art transposition models. This paper uses surface measurements at the Solar Resource Research Laboratory (SRRL) of National Renewable Energy Laboratory (NREL) to analyze the performance of the isotropic and empirical models and explore the physics behind their uncertainties[10, 11]. This study should be useful in improving the accuracy in the development of future physics-based models.

## 2. TRANSPOSITION MODELS

Transposition models express POA irradiance on an inclined surface by

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

where $POAI_d$, $POAI_{u,sky}$, and $POAI_{u,ground}$ represent the POA irradiances related to direct solar radiation, downwelling diffuse solar radiation, and solar radiation reflected by land surface and reaching the PV panel, respectively.

$POAI_d$ is essentially the component of direct solar radiation in the normal direction of a PV panel as follows:

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

where $\theta'$ is the angle between the direct solar radiation and the normal direction of the PV panel. The value of $\theta'$ can be solved by rotating a PV plane from the horizontal position to an inclined position:

$$\cos\theta' = \cos\beta\cos\theta + \sin\beta\sin\theta\cos\varphi \tag{2b}$$

where $\theta$ is solar zenith angle, $\varphi$ is the relative azimuth angle, and $\beta$ is the tilt angle of the PV panel.

Liu and Jordan[6] analytically derived diffuse sky radiation with isotropic radiances:

$$POAI_{u,sky} = DHI\frac{1+\cos\beta}{2} \tag{3a}$$

which has been widely used in solar energy applications. The corresponding POA irradiance from surface reflections is

$$POAI_{u,ground} = GHI\sigma\frac{1-\cos\beta}{2} \tag{3b}$$

where σ is land surface albedo.

A well-known empirical model to compute diffuse POA irradiance was developed by Perez et al. [3] (hereafter referred to as PEREZ) wherein isotropic diffuse, circumsolar and horizon brightening radiation were considered with comprehensive sets of coefficients determined from various climatic environments. Details on PEREZ are not restated here because they are described by Perez et al.[3].

## 3 RESULTS

We investigated 1-minute GHI, DNI, DHI, and surface albedo measurements at NREL. The isotropic model based on Eqs.(1-3) is combined with the surface measurements to simulate POA irradiance. The simulations are then compared to POA irradiance measured by a Kipp and Zonen CM 11 Pyranometer (CMP 11) and IMT Solar reference cell (IMT) on a 1-axis tracker located at NREL.

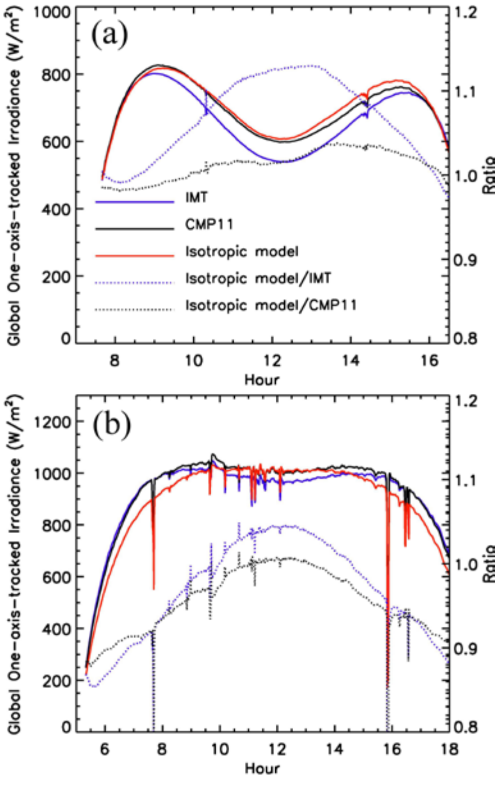

Figure 1 Comparison of POA irradiances from the model simulation to measurements at NREL (a) "winter day (b) summer day.

Figure 1 compares POA irradiances simulated by the isotropic model and measurements on 1/22/2015(a "winter" clear-sky day) and 7/30/2015 (a "summer" clear-sky day). The dashed lines represent ratios of model simulation to measurements. As shown in Fig.1a, the isotropic model agrees well with the measurements. Compared to CMP 11, the relative error of the isotropic model is within 3%. However, the POA irradiance from the IMT is systematically smaller than both the CMP 11 measurements and the model simulations, which is probably caused by angle of incidence effects and measurement biases due to spectral differences between calibration and measurement conditions. In this case the magnitude of the difference is more pronounced at noon than it is during the morning and evening. Compared to CMP 11, smaller POA irradiances observed by IMT are also shown in Fig.1b. In addition, the uncertainty from the isotropic model becomes more obvious in summer. Fig.1b shows that the simulation using the isotropic model can underestimate the POA irradiance by up to 20% when compared to both the IMT and CMP 11 measurements.

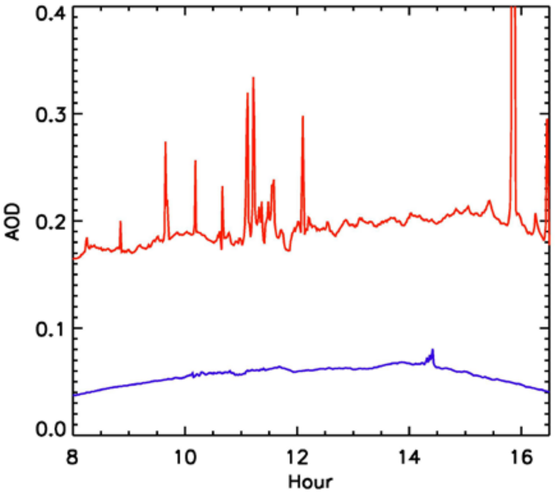

Figure 2 AODs on 1/22/2015 "winter" (blue) and 7/30/2015 "summer" (red).

The variation of the uncertainty in the isotropic model should also be related to the variation on aerosol optical depth (AOD). Figure 2 shows the AODs on 1/22/2015 and 7/30/2015 from NREL's measurements. Greater uncertainty of the isotropic model is associated with greater AOD. When the AOD is negligible, diffuse radiation in the atmosphere is mainly caused by Rayleigh scattering, wherein the spatial distribution of the scattered radiation is not sensitive to the scattering angle. For a larger AOD, using the isotropic model results in more uncertainty because the light scattering by aerosol is more significant in the forward direction compared to other directions resulting in higher anisotropic scattering.

Figure 3 compares the CMP 11 measurements on 1/22/2015 to the simulations by PEREZ. The colors in the figure represent PEREZ from different empirical coefficients. As shown, the simulated POA irradiances from PEREZ that have different empirical coefficients can be substantially different indicating that the selection of proper empirical coefficients is critical. Compared to the isotropic model shown in Fig. 1a, PEREZ does not show better performance unless the optimal coefficients are used. Thus, the isotropic model can be still used as a reference when empirical coefficients from PEREZ lead to substantial biases.

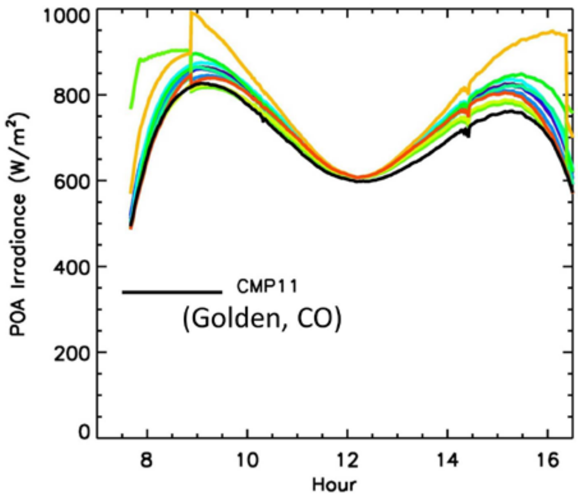

Figure 3 Comparison of POA irradiance from CMP 11 measurements on 1/22/2015 (winter) and PEREZ with different empirical coefficients.

In addition to the empirical coefficients, other input properties in transposition models also affect their accuracy. Decomposition models, e.g. DISC model, are routinely used to compute DHI and DNI, and they are used as inputs to transposition models. The simulated properties can bring additional uncertainties to POA irradiances. Figure 4 shows the difference between the PEREZ simulations with optimal coefficients and CMP 11 measurements on 1/22/2015. The solid line is associated with simulations using surface measurements of DHI, whereas the dashed line represents the simulations from computed DHI by DISC model. As shown, using the computed DHI brings additional uncertainty in the POA irradiance—by up to 80 W/m$^2$. This uncertainty is more obvious in the morning and evening when more diffuse radiation is available.

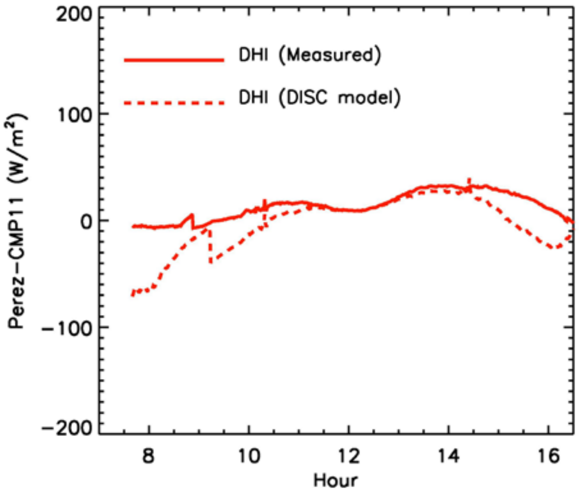

Figure 4 Difference between POA irradiances simulated by PEREZ and measured at NREL on1/22/2015. DHIs used for PEREZ are from surface measurements (solid) or computed by DISC model.

## 4. CONCLUSIONS

This study analyzes the performance of transposition models simulating solar radiation on inclined surfaces. Surface measurements of solar radiation on horizontal surfaces were used as inputs of an isotropic model and an empirical model, PEREZ, to compute the POA irradiances and compare them to those measured by the 1-axis CMP 11 and IMT. Our results indicate that the isotropic model is associated with larger uncertainty for larger AODs. However, the isotropic model plays an important role in transposition models because the use of empirical coefficients in the PEREZ model may lead to significantly different uncertainties when simulating the POA irradiance. The use of computed DHI and DNI from decomposition models may bring additional uncertainties to POA irradiance estimates.

## 4. ACKNOWLEDGEMENTS AND DISCLAIMER

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