Evaluation of Models and Measurements to Estimate Solar Radiation for 1-Axis Tracking Modules at NREL's SRRL

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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Evaluation of Models and Measurements to Estimate Solar Radiation for 1-Axis Tracking Modules at NREL's SRRL

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***Abstract*—Solar radiation reaching photovoltaic (PV) modules on a 1-axis tracking system can be measured by reference cells or thermopiles. The former is often biased due to the reflection of solar radiation by the glass cover of the PV. The uncertainty can be moderated by applying a correction factor, as a function of solar incident angle and the refractive index of the glass, to the measurement. On the other hand, solar radiation on the inclined PV panels can be computed by transposition models using global horizontal irradiance (GHI) observations from thermopiles. This study examines the models and measurements to estimate solar radiation for 1-axis tracking modules at the National Renewable Energy Laboratory's (NREL's) Solar Radiation Research Laboratory (SRRL). The 1-minute plane-of-array (POA) irradiances from 2019 are computed using the observed GHIs and a transposition model developed by Perez et al. The POA irradiances are compared with the observation by an IMT reference cell and a Kipp & Zonen CM Pyranometer 22 (CMP22) thermopile. For the SRRL's 1-axis tracking system with an annual solar energy of 2323.9 kWh/m^2, the POA irradiance is overestimated by ~70 kWh/m^2 using the transposition model. This bias is reduced by more than 50% using the IMT measurements calibrated by a correction factor for a PV surface of antireflection coated glass.**

Keywords—solar radiation, POA irradiance.

I. INTRODUCTION

Solar radiation is routinely measured or computed on horizontal surfaces; however, for greater solar energy gain, photovoltaic (PV) modules are often inclined with respect to the horizontal plane to reduce the solar incident angle [1]. In contrast to PV modules with fixed tilt angles, they can also be mounted on a solar tracking system, either rotating along a single axis or having two degrees of freedom to more closely follow the sun's daily east-west motion as well as the seasonal north-south motion. The global solar irradiance reaching the inclined PV modules are often referred to as the plane-of-array (POA) irradiance.

Plane-of-array (POA) irradiance can be simulated by transposition models in various orientations using measurements of global horizontal irradiance (GHI) and direct normal irradiance (DNI) [2]. An obvious drawback of such models is that the regression functions determined by long-term observations of surface radiation are challenged by the complexity of diffuse radiation that is scattered by air molecules, aerosols and clouds in the atmosphere and partially reflected by the land surface [3-19]. To overcome this bias, Xie and Sengupta [3] and Xie et al. [4] proposed a physics-based solution of POA irradiances in 2002 wavelengths using the precomputed cloud transmittance of solar radiance and satellite estimated atmospheric properties [20, 21].

POA irradiance can be observed at the land surface by thermopiles or reference cells. The accuracy of the latter is affected by the energy reduction as the reflection/scattering of the glass surface varies with the solar incident angles. To compensate for this reduction in the observation, a correction factor was introduced as a function of solar incident angle and type of PV coating. Marion [22] provided a numerical solution to compute the angle-of-incidence (AOI) correction factor for diffuse radiation from the atmosphere and land surface. The AOI correction factor for direct radiation was computed on the basis of Snell's law and Fresnel equations. With the assumption of isotropic diffuse radiation from the sky and land surface, the overall AOI correction factor for diffuse radiation was given by integrating radiances in differential solid angles within the field of view.

To understand the performance of the models and measurements by PV modules on the estimation of POA irradiance, this study analyzes 1-year data at the National Renewable Energy Laboratory's (NREL's) Solar Radiation Research Laboratory (SRRL). The models and measurements by PV modules are evaluated using POA irradiance observed by a thermopile mounted on a 1-axis tracking system.

II. EVALUATION OF POA IRRADIANCE USING SRRL DATA

2.1 Data and algorithm

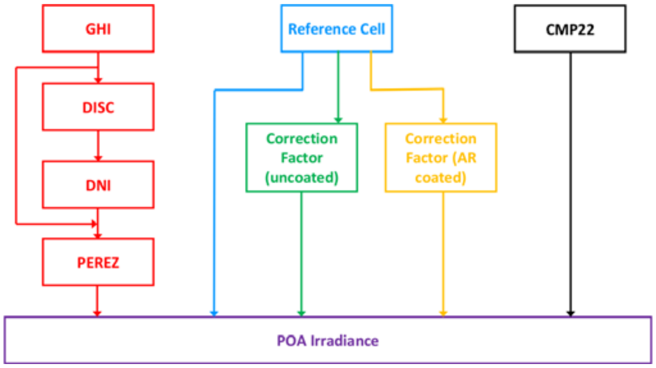

Figure 1 A flowchart of computing POA irradiance and compared it with surface observations.

To examine the transposition models and measurements of POA irradiance by reference cell, we collected 1-minute resolution observations from a Kipp & Zonen CM Pyranometer 22 (CMP22) thermopile and an IMT reference cell on a 1-axis tracking system at NREL's SRRL. For the model simulation, the 1-minute surface pressure and GHI data observed by a horizontal CMP22 were also collected from 2019. Figure 1 shows a flowchart of computing the POA irradiances and compared them with surface observations. The Direct Insolation Simulation Code (DISC) [23] is first applied to the measured GHI to compute DNI. The GHIs, DNIs and surface pressure are then used by the Perez model to numerically calculate the POA irradiance for a PV module on a 1-axis tracking system. The POA irradiance is observed by the IMT reference cell. Following the numerical model reported by Marion [22], the energy reduction by the PV surface reflection is taken into account by using the AOI correction factors for diffuse radiation associated with uncoated and antireflection (AR) coated glass. The model simulation and corrected observation are compared with the observation from the CMP22 thermopile on the 1-axis tracker.

2.2 Evaluation using SRRL data

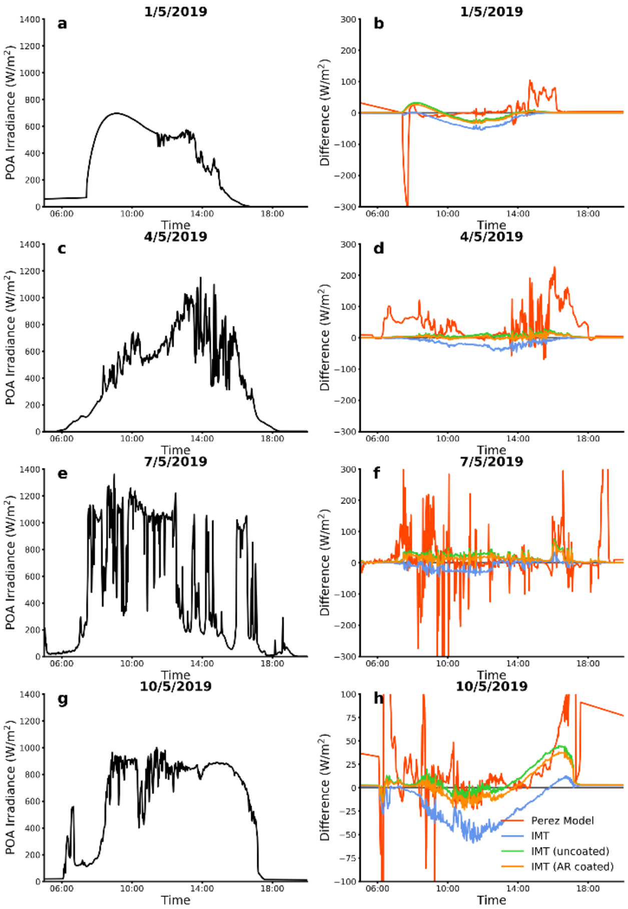

Figure 2 POA irradiances measured by a CMP22 and their differences from those provided by the Perez model and IMT.

Figure 2 compares the POA irradiances from the model simulation and observation. Compared to the IMT data for the selected 4 days, the computation by the Perez model shows greater deviation than the more precise observation by the CMP22 instrument deployed in the POA, especially under cloudy-sky conditions. It can also be seen that the IMT observation without a correction of the PV surface reflection underestimates the POA irradiance. The underestimation becomes more obvious at noon compared to the other time as PV surface reflection is determined by the solar incident angle and the magnitude of the POA irradiance. The noon time is usually associated with smaller correction factors for PV surface reflection and greater solar radiation. With the correction of the PV surface reflection, the energy reduction is moderated, so the correction factor for the AR coated glass leads to a smaller bias.

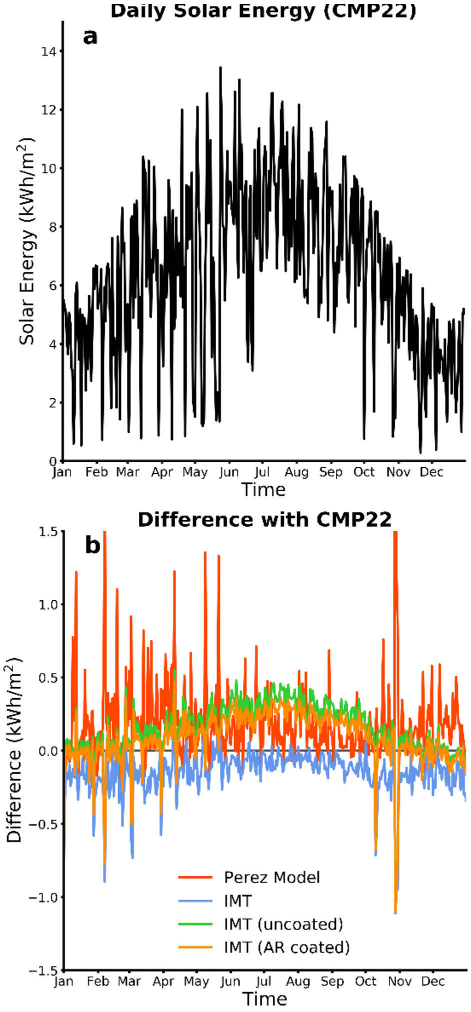

Figure 3 (a) Daily averaged solar energy measured by a CMP22 on a 1-axis tracker; and (b) their differences with those provided by the Perez model and IMT.

The consequence is consistent in long-term data as shown in Fig. 3 where the daily averaged solar energy is compared over 2019. The 1-minute resolution data from the model simulation and the IMT measurements are compared with the CMP22 in Fig. 4, where the green line represents the regression of the data. Based on the mean bias error (MBE), mean absolute error (MAE), percentage error (PE), and absolute percentage error (APE), the Perez model slightly overestimates POA irradiance and leads to a greater deviation from the CMP22 measurements. The correction factors for the PV surface reflection effectively reduce the measurement uncertainty from the IMT reference cell. The correction factor related to the AR coated glass reduces the IMT measurements by approximately 50% according to the MBE and PE values.

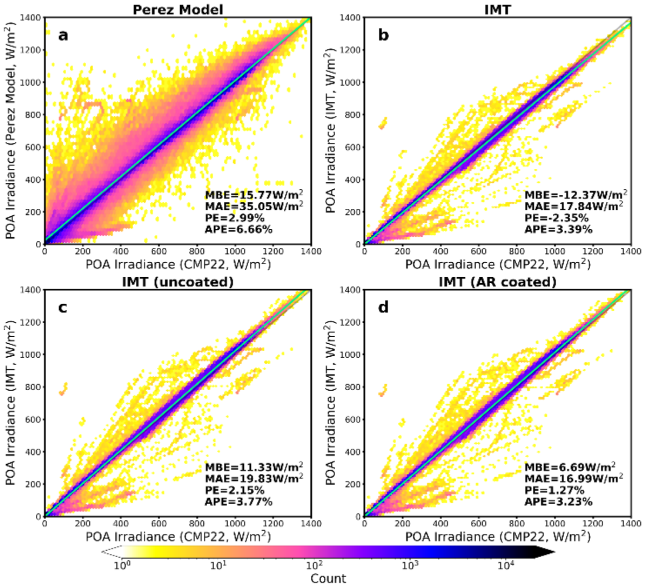

Figure 4 Comparisons of POA irradiances measured by a CMP22 with those provided by the Perez model and IMT.

III. CONCLUSIONS

This study evaluates the models and measurements by a reference cell to estimate POA irradiance for a 1-axis tracking system. The DNI data were computed using the DISC model and 1-minute resolution GHI measured using a horizontal CMP22 at NREL's SRRL. The GHI, DNI, and surface pressure were used by the Perez model to compute POA irradiance for a 1-axis tracking system. The computed POA irradiance is compared with the measurement from an IMT reference cell at NREL's SRRL. To reduce the bias from PV surface reflection, a correction method for two types of PV surface coating was applied to the IMT data. The model simulation and measurements by the IMT reference cell were further evaluated using the more accurate observation by measurements from a CMP22 deployed in the POA. It was observed that the corrected reference cell provides more accurate POA estimates compared to the POA irradiance calculated using a GHI measurement.

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