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Recent Advancements in the Numerical Simulation of Surface Irradiance for Solar Energy Applications

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Abstract—**This paper briefly reviews the National Renewable Energy Laboratory's recent efforts to develop all-sky solar irradiance models for solar energy applications. The Fast All-sky Radiation Model for Solar applications (FARMS) uses the simulation of clear-sky transmittance and reflectance and a parameterization of cloud transmittance and reflectance to rapidly compute broadband irradiances on horizontal surfaces. The accuracy of FARMS is comparable to that of two-stream approximation, but it is approximately 1,000 times faster. A FARMS for Narrowband Irradiance over Tilted surfaces (FARMS-NIT) has been developed to compute spectral irradiances on photovoltaic (PV) panels in 2,002 wavelength bands. FARMS-NIT has been extended to bifacial PV panels by accounting for solar radiation reaching the backside of a PV panel.**

I. Introduction

Multiple radiative transfer models that simulate atmospheric radiation under all-sky conditions have been developed and used in a broad range of applications, such as climate and weather studies [1]. Compared to those applications, radiative transfer models for solar energy applications have unique requirements; thus, specific prerequisites are inherent in the model design. For instance, radiative transfer models for climate and weather studies provide broadband irradiances only in direct, upwelling, and downwelling directions or radiances in narrow-wavelength bands [2, 3]. In contrast, solar energy applications require solar irradiances over inclined surfaces because solar systems track the sun on multiple axes. Because of the spectral response of photovoltaic (PV) panels, irradiances in numerous narrow-wavelength bands are particularly desired for solar cell research. In addition, solar resource assessment and forecasting studies require extremely fast and efficient computations because irradiance changes rapidly during time and space, and fast computations at high resolutions are required for large geographic areas.

During recent decades, a significant number of solar irradiance models have been developed for and actively used by solar energy applications [4-6]; however, many of them lack the ability to simulate solar irradiance under clouds, which cover approximately 70% of the Earth's surface at any given time [7]. Solar irradiance models that have taken clouds into account in broadband or spectral irradiance simulations [8] have represented the complex processes of absorbing and scattering by clouds by using empirically determined cloud-modification factors that are less accurate compared to the physical solutions of radiative transfer models for climate and weather studies. Thus, there is a critical need for advanced models that can bridge the special demands of solar energy applications and the advantage of radiative transfer models for climate and weather studies.

This study briefly introduces the National Renewable Energy Laboratory's (NREL's) recent advancements in rapid broadband and spectral radiative transfer models to meet the requirements of solar energy applications. The rest of this paper is organized as follows. Section 2 summarizes the rapid simulation of solar irradiance over horizontal surfaces. Section 3 discusses the efforts to simulate narrowband irradiances over inclined PV panels and those consisting of bifacial PV modules. The last section summarizes the results and future studies.

II. Rapid Simulation of Shortwave Irradiances over Horizontal Surfaces

A Fast All-sky Radiation Model for Solar applications (FARMS) [9] was developed to compute broadband diffuse horizontal irradiance and direct normal irradiance (DNI). The cloud transmittance and reflectance of solar irradiance are precomputed by the Rapid Radiation Transfer Model [1] for all possible cloud conditions and solar and viewing geometries. They are parameterized using exponential functions, and are combined with clear-sky transmittances and reflectances of irradiance to rapidly compute broadband irradiances for all-sky conditions. Details of FARMS are not restated here because they are extensively given in [9].

The clear-sky tranmisttance and reflectance are computed using the clear-sky irradiance model REST2 [4]. The accuracy of FARMS is comparable to or better than the two-stream approach, but it is approximately 1,000 times more efficient. We recently implemented the Bird Clear-Sky Model [6] (hereafter referred to as BIRD) in FARMS. Our investigation indicated that using FARMS with BIRD is consistantly accurate as validated by surface measurements, but the computational efficiency increases by more than 100% compared to using FARMS with REST2 as the clear-sky model.

III. Narrowband Irradiances over Inclined PV Panels

To extend the capability of FARMS, we recently developed the FARMS for Narrowband Irradiances over Tilted surfaces (FARMS-NIT) to efficiently compute spectral plane-of-array (POA) irradiances received by PV panels. A comprehensive lookup table of cloud bidirectional transmittance distribution functions (BTDFs) was developed using LibRadtran [10]. To account for multiple reflections between cloud and land surface, we also computed the cloud transmittance and reflectance of spectral irradiances. They were then combined with a clear-sky model, SMARTS [5], to compute all-sky radiances.

A. Narrowband Irradiances over Monofacial PV Panels

From the simulation of radiances, solar irradiance in the POA can be given by:

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

where $POAI_d$, $POAI_{u,sky}$, and $POAI_{u,ground}$ represent the POA irradiances from direct solar radiation, diffuse sky radiation, and solar radiation reflected by the land surface that reaches the PV panel, respectively.

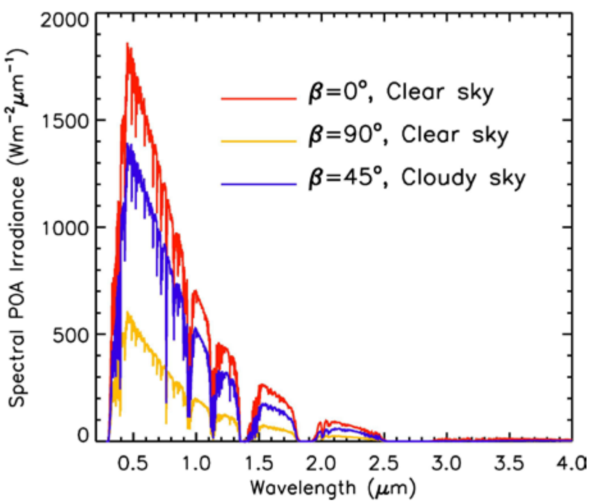

Fig. 1. Spectral POA irradiance for a solar zenith angle of 15º.

$POAI_d$ is given by the direct solar radiation in the normal direction of the PV panel, as follows:

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

where θ' is the angle between the direct solar radiation and the normal direction of the PV panel. $POAI_{u,sky}$ can be given by the integration of radiances in the perpendicular direction to the tilted PV panel:

$$POAI_{u,sky} = \int_0^{2\pi}\int_0^{\Theta} I \cos\theta' \sin\theta d\theta d\varphi \tag{3}$$

where I is the radiance, and Θ denotes the upper limit of θ. The contribution from the reflected solar radiation by land surface can be given by:

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

where I_r is reflected radiance by land surface.

In FARMS-NIT, we follow the wavelengths from SMARTS because they are used to compute the clear-sky transmittance and reflectance; thus, 2,002 narrow-wavelength bands are considered. An example output from FARMS-NIT is shown in Fig. 1, where β represents the tilt angle of the PV panel. For the cloudy sky, we assume a water cloud with an optical thickness of 3 and an effective particle diameter of 20 μm.

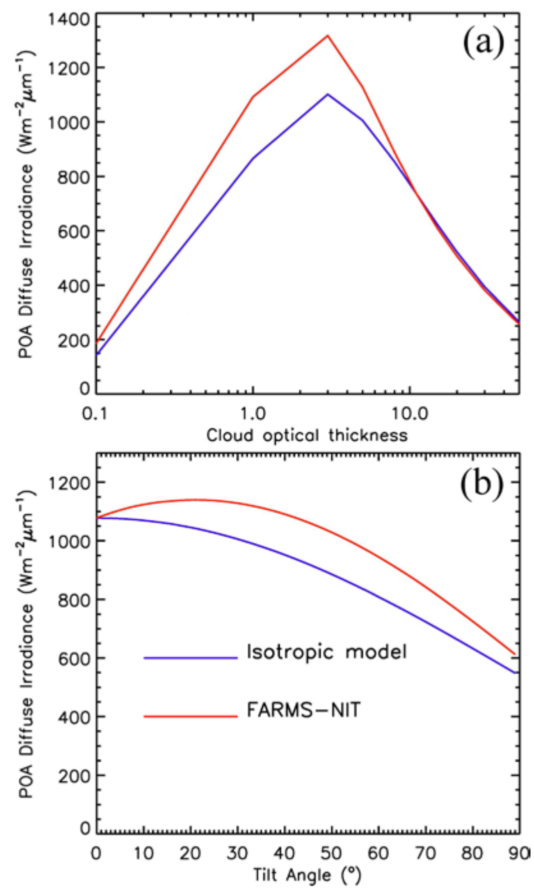

Fig. 2. (a) POA diffuse irradiances for β=30° and water clouds with various cloud optical thickness and (b) those for a cloud optical thickness of 5 and various β. The wavelength λ=0.6 μm. We assume a solar zenith angle of 30º and water clouds with an effective particle diameter of 20 μm.

Compared to FARMS-NIT, models assuming isotropic distribution of diffuse radiation might dramatically underestimate POA irradiance due to the neglect of the stronger forward scattering by clouds (see Fig.2a). The underestimation increases with cloud optical thickness, but it rapidly decreases when the clouds are thick. For λ=0.6 µm and a solar zenith angle of 30°, the underestimation can reach more than 20%. Figure 2b shows that the underestimation by the isotropic model reaches the maximum when the tilt angle is around the solar zenith angle because the maximum of direct POA irradiance received by the PV panel.

B. Narrowband Irradiances over Bifacial PV Panels

Because radiances in the atmosphere are computed by FARMS-NIT, this model can be extended for the simulation of POA irradiances on bifacial PV panels. Similar to (1), the POA irradiance on the backside of a bifacial PV is:

$$POAIB = POAIB_d + POAIB_{u,sky} + POAIB_{u,ground} \tag{5}$$

$POAIB_d$, $POAIB_{u,sky}$, and $POAIB_{u,ground}$ are the backside irradiances from the direct solar radiation, diffuse sky radiation, and land-surface reflection, respectively. With the radiation in the perpendicular directions on the backside of the PV panel, $POAIB_d$, $POAIB_{u,sky}$, and $POAIB_{u,ground}$ can be derived as follows:

$$POAIB_d = \begin{cases} -DNI\cos\theta' & for \quad \cos\theta' < 0 \\ 0 & for \quad \cos\theta' \geq 0 \end{cases} \tag{6}$$

$$POAIB_{u,sky} = -\int_0^{2\pi}\int_{\Theta}^{\frac{\pi}{2}} I\cos\theta'\sin\theta d\theta d\varphi \tag{7}$$

$$POAIB_{u,ground} = \int_0^{2\pi}\int_{\frac{\pi}{2}-\Theta}^{\frac{\pi}{2}} I_r\cos\theta'\sin\theta d\theta d\varphi \tag{8}$$

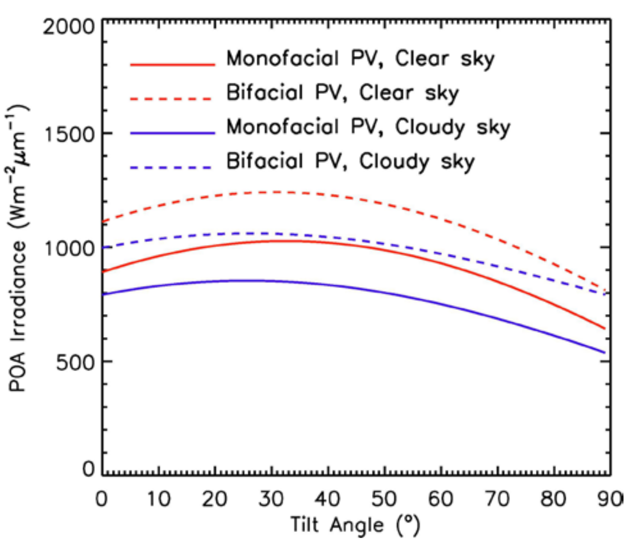

Fig. 3. POA irradiances over monofacial and bifacial PV panels for a solar zenith angle of 30° and a land-surface albedo of 0.25. For the clear-sky condition, AOD is 0.5. For the cloudy-sky condition, a water cloud with cloud optical thickness of 3 and effective particle diameter of 10 µm is assumed.

We consider a single monofacial or bifacial PV panel where solar shadow from the PV panel itself and nearby PV panels is neglected. The surface-reflected radiance can then be approximated as

$$I_r = \frac{GHI\sigma}{\pi} \tag{9}$$

where σ denotes land-surface albedo.

Figure 3 shows the POA irradiances simulated for clear- and cloudy-sky conditions when the solar zenith angle is 30° and the land-surface albedo is 0.25. For the clear-sky condition, the aerosol optical depth (AOD) is 0.5. When clouds are present, a water cloud with the optical thickness of 3 and effective particle diameter of 10 µm is assumed. The POA irradiances are computed for the 2,002 spectral bands and integrated to give the broadband irradiances from 0.28-4.0 µm as shown in Fig. 3. Also shown is that bifacial PV panels receive significantly more solar radiation than monofacial PV panels because of the radiation reaching the backside of the PV panels after being scattered in the atmosphere or reflected by the land surface. For the clear-sky condition, the bifacial PV panel receives 21.88% more solar radiation compared to the monofacial PV panel. For the cloudy-sky condition, the bifacial PV panel receives 28.42% more solar radiation because of greater diffuse irradiance scattered by clouds.

Note that greater land-surface albedo will further increase the POA irradiances, especially for bifacial PV panels; however, solar shadows because of PV panels decrease the global horizontal irradiance (GHI) reaching the land surface and thus more significantly affect bifacial PV panels receiving much more reflected solar radiation than monofacial PV panels. This effect depends on the size, geometry, and tilt angles of the PV panels as well as their density and displacement over the area, which should be investigated by a parallel research effort.

IV. Conclusions

Conventional radiative transfer models for climate and weather studies differ from solar irradiance models for solar energy. Although the former can precisely simulate solar irradiance for all-sky conditions by solving the radiative transfer equation, they do not meet the requirements for solar energy applications. In this paper, we briefly reviewed NREL's recent efforts to improve the radiative transfer models for efficient solar energy applications. We developed FARMS using a clear-sky model and a parameterization of cloud transmittance and reflectance. We discovered that the clear-sky models REST2 and BIRD provide comparable accuracy when used by FARMS. The computational efficiency of FARMS increased by more than 100% when REST2 was replaced with BIRD. Because FARMS provides rapid and accurate solutions of GHI and DNI, it has been used in a number of applications since its development (e.g., NREL's

National Solar Radiation Database and the Weather Research and Forecasting model for solar energy forecasts). We extended the capability of FARMS by developing FARMS-NIT to compute spectral irradiances over both horizontal and tilted surfaces. The irradiances on tilted surfaces are provided by a lookup table of cloud BTDFs and a spectral irradiance model for clear-sky conditions. We also demonstrated the capability of FARMS-NIT to compute POA irradiances over bifacial PV panels.

FARMS and FARMS-NIT as a whole have bridged the special demands of solar energy and the advantages of radiative transfer models for climate and weather studies. Further improvements to and the applications of these models will provide opportunities to improve the availability and accuracy of solar resource assessments and forecasts.

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