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Analysis of Irradiance Models for Bifacial PV Modules

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Abstract — We describe and compare two methods for modeling irradiance on the back surface of rack-mounted bifacial PV modules: view factor methods and ray-tracing simulations. For each method we formulate one or more models and compare each model with irradiance measurements from reference cells mounted on the back of PV modules in various configurations. Our analysis illustrates the relative contribution of different components (sky diffuse, ground reflected, and reflections from nearby PV structures) to the global back surface irradiance, examines the importance and effects of various modeling assumptions, and quantifies the accuracy of each modeling approach.

***Index Terms* — bifacial PV module, irradiance, ray tracing, view factor.**

I. Introduction

Bifacial photovoltaic (PV) cells, modules, and systems potentially offer a rapid pathway to significantly lower levelized cost of energy. Bifacial PV arrays are not widely deployed in part because their potential performance advantages are not generally understood. Sandia National Laboratories, the National Renewable Energy Laboratory and the University of Iowa are investigating bifacial PV performance and characterization in a joint project funded by the US Department of Energy. The project's main objectives are (1) measure the performance of various bifacial PV technologies using an outdoor test bed, (2) develop and validate models of back surface irradiance, and (3) work with industry to develop rating standards for bifacial PV modules. The outdoor test bed being built at Sandia in Albuquerque, NM will allow investigation of the many factors that influence bifacial PV performance, including ground albedo and array geometry (e.g., height above ground, tilt angle, row position, row-to-row spacing).

Conceptually, total irradiance on the back surface of a rack-mounted module results from the combination of:

- Sky diffuse irradiance. The visible sky depends on the module's tilt and azimuth and is restricted by other nearby structures.
- Ground-reflected irradiance which can vary across the surfaces behind the module due to albedo and the irradiance incident on the ground surfaces.
- Structure-reflected irradiance from nearby objects such as from the front of PV modules in an adjacent row.
- Direct irradiance on the back surface, e.g., when the sun elevation is low and the sun azimuth is behind the front plane of the array.

In our paper we will describe measurements of global irradiance on the back surface of modules for several array configurations. We will present two different approaches (view factor and ray tracing) to model back surface irradiance and will compare each model with measurements, analyzing the relative importance of each model's features and summarizing each model's accuracy.

II. Measured Back Surface Irradiance

The National Renewable Energy Laboratory is measuring irradiance using reference cells mounted on the back surface of several arrays. Figure 1 illustrates a pedestal-mounted array at NREL which comprising eight modules in two rows of four, oriented south at approximately 40° tilt about 1m from the ground, with three reference cells mounted along a vertical strip roughly halfway between the array center and its western edge.

Fig. 1. Back surface irradiance measurement locations on the NREL array.

Measured back surface irradiance is also being obtained for a close-mount rooftop system over two different roofing materials and a ground-mount, fixed rack array over grass and gravel.

Figure 2 illustrates measured back surface irradiance at each reference cell on the pedestal-mounted array during a day with clear sky conditions. Back surface irradiance is greater in the afternoon than morning as the array's shadow moves farther from the measurement locations. The variation among the locations at a given time requires further investigation.

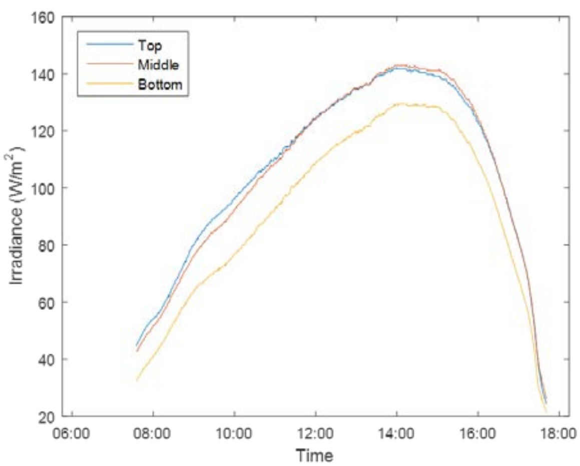

Fig. 2. Back surface irradiance measured on Sept. 12 at the NREL array.

III. Back Surface Irradiance Models

Back surface irradiance models are classified here as either view factor models or ray tracing simulations. Compared to ray tracing simulations, view factor models are less demanding computationally and require few parameters but represent a PV system with less detail.

A View Factor Models

View factors, also termed shape and configuration factors, quantify the fraction of irradiance reflected from one surface that arrives at a receiving surface. View factor models [1], [2] calculate a component (e.g., structure-reflected irradiance) contributing to total back surface irradiance E_2 (W/m^2) using the following general formula:

$$E_2 = G_1 \times VF_{1\to2} \qquad (1)$$

where G_1 is the total irradiance on the reflecting area being considered (e.g., adjacent row) and $VF_{1\to2}$ is the view factor from the reflecting area to the back surface of the module. The total irradiance on the back surface of a module is the sum of the component irradiances. A view factor model implicitly assumes that all reflecting surfaces are Lambertian, i.e., irradiance is scattered isotropically.

We formulate an array-scale model which neglects edge effects and a more detailed model which accounts for row and cell position. The array scale view factor model may be appropriate when variation in back surface irradiance along a row is insignificant with respect to the overall energy production. Figure 3 illustrates the components of irradiance considered in the array scale model which include: sky diffuse irradiance from the visible wedge of the sky accounting for circumsolar, horizon and rest-of-sky diffuse irradiance; ground reflected irradiance accounting for shading of the ground by the array; and reflected irradiance from the front surface of adjacent rows. The array scale model can estimate variation in back surface irradiance along the vertical dimension of a module, but not along its lateral dimension.

The detailed view factor model extends the array scale model by accounting for the module's position within the array and the lateral dimensions of the module. Figure 4 illustrates the irradiance components considered by the detailed view factor model.

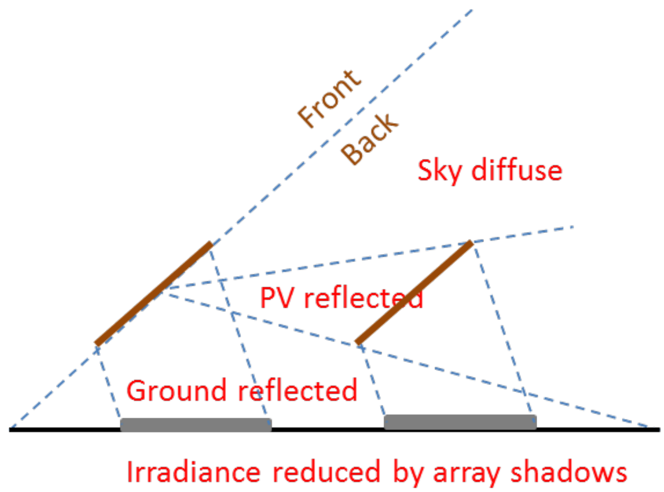

Fig. 3. Irradiance components considered in the 2D geometric model.

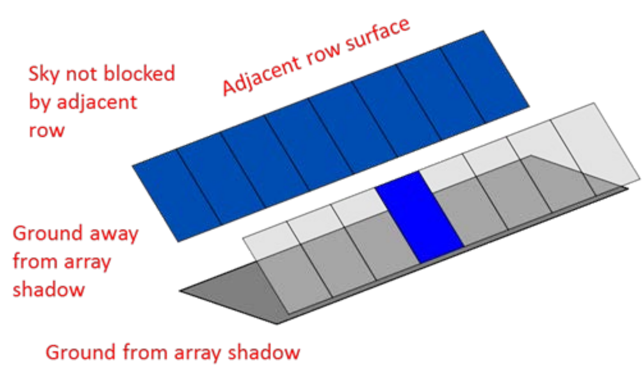

Fig. 4. Irradiance components considered in the detailed view factor model.

The structure-reflected irradiance component depends on position within the array; intuitively, modules near the middle of a row should see more reflected irradiance than modules at the ends of a row. Similarly, modules near the ends of a row should see greater sky diffuse irradiance than would a module in the row's middle, because less of the sky is blocked from view by nearby rows. Shadows from the array reduce the irradiance scattered from parts of the ground nearby the module of interest and thus affect the ground-reflected component of back surface irradiance.

B Ray Tracing Simulations

Ray tracing models simulate the propagation of electromagnetic waves in systems in which the wavelength is much smaller than the smallest geometric detail, as is the case for modeling PV arrays interacting with visible wavelengths (300 nm to 750 nm). The electromagnetic waves are treated as rays that can propagate through homogeneous or graded media; ray trajectories can be computed over long distances at a low computational cost because it is not necessary to resolve the wavelength. Rays may be reflected or refracted at boundaries between different media.

Ray tracing simulations can potentially explore the effects of detailed features in module and array design, such as spacing between modules and/or a module's cells, which cannot be easily addressed in the view factor models. Monte Carlo methods are commonly used to propagate a large number of possible rays to arrive at irradiance on the different surfaces in the modeled system. We are developing simulations of several PV array geometries using the open source software RADIANCE [3] which provides physically realistic image rendering and illuminance mapping, and has been used previously for the modeling of bifacial PV installations [4]. We are also investigating the use of COMSOL's Ray Optics module, which differs from RADIANCE in that it traces rays from the source to the observer while RADIANCE performs the tracing in reverse.

IV. Preliminary Analysis

Figure 5 illustrates the detailed view factor model of an array comprising a single row of eight modules. We observe a 50% variation in back surface irradiance across the module at the end of the array. Irradiance is more uniform for modules interior to the row, although the bottom-to-top variation along any of these modules is still on the order of 30%. Mismatch in current from a string's cells due to the irradiance variation may reduce power from the back surface of a module.

Figure 6 shows preliminary modeling parameters (left) and COMSOL simulations results (right) for a single 60-cell monocrystalline silicon (c-Si) PV module. Optical properties of the various surfaces of the installed module are obtained from literature or from field data obtained from NREL. The refractive index values represent NREL's measurements of reflectivity of a soiled beige roof. Simulation results for direct normal incidence of light at 600 nm wavelength indicate the intensity of irradiance reflecting off the soiled beige roof onto the back of the module.

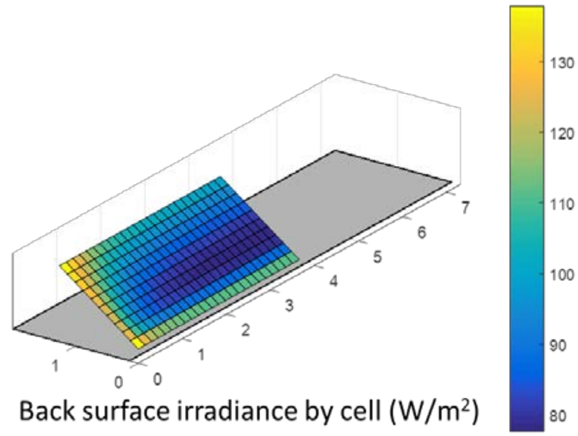

Fig. 5. Variation in back surface irradiance across a single row of modules at fixed tilt and solar noon.

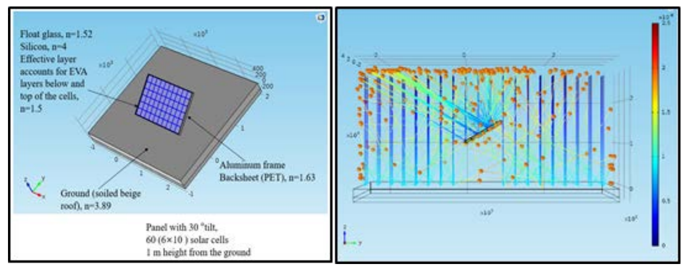

Fig. 6. PV module modeling setup in COMSOL Ray Optics module (left); ray trajectories for a PV module exposed to direct normal incidence light (right).

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