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 models and ray-tracing simulations. For each method we formulate one or more models and compare each model with irradiance measurements and short circuit current for a bifacial module mounted a fixed tilt rack with three other similarly sized modules. Our analysis illustrates the computational requirements of the different methods and provides insight into their practical applications. We find a level of consistency among the models which indicates that consistent models may be obtained by parameter calibrations.

***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 to the northeast or northwest of a south-facing array.

Here we describe two methods for modeling irradiance on bifacial PV modules: view factor models, including a cell level and an array scale model, and ray tracing models using the RADIANCE and COMSOL software packages. We compare results from the cell level view factor model and ray tracing models with measured irradiance and short circuit current for a small array of four modules, two of which are bifacial, to illustrate the application of each approach.

III. 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. Lower irradiance at the bottom cell is likely due to the electrical boxes which block the cell's view of ground and sky diffuse irradiance to a greater extent than for the other two cells.

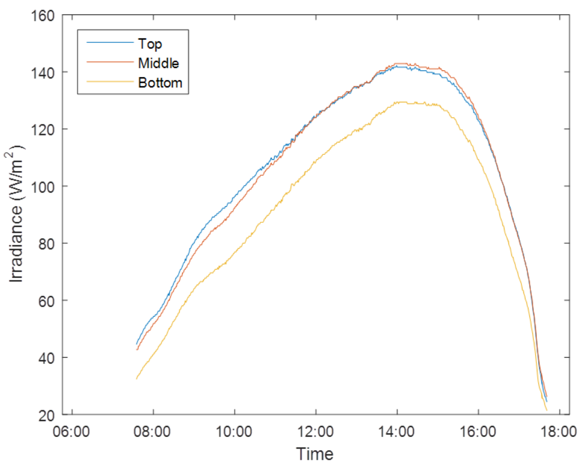


Fig. 2. Back surface irradiance measured on Sept. 12 at the NREL array.

Fig. 3. Bifacial modules (right) on test rack at Sandia National Laboratories.

Figure 3 shows a test rack at Sandia National Laboratories with a pair of bifacial and conventional modules. Reference cells are mounted coplanar with the modules along the center of the rack, two facing sunward and three facing rearwards. We use data from these modules to compare modeled irradiance to module short circuit current.

II. 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.

II.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:

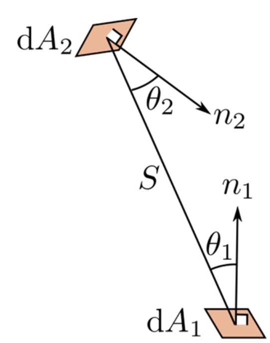
$$E_2 = G_1 \times VF_{1\rightarrow 2} \qquad (1)$$

where G_1 is the total irradiance (W/m^2) on the reflecting area being considered (e.g., adjacent row) and $VF_{1\rightarrow 2}$ is the view factor (unitless) 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 a cell level view factor model that estimates irradiance on the back surface of each cell in an array. Figure 4 illustrates the irradiance components considered by the detailed view factor model. View factors are calculated by integration (Eq. 2) using terms in the illustration. Irradiance on the sunlit ground is modeled by global horizontal irradiance (GHI); irradiance on the shadowed area is modeled by diffuse horizontal irradiance (DHI); reflection from the adjacent row is modeled by applying the model of Martin and Ruiz [3] to direct normal irradiance (DNI). Sky diffuse irradiance and ground reflected irradiance (from sunlit and shadowed areas) are considered isotropic. The cell level model is implemented in Matlab and computation is reasonably fast, e.g., simulation

$$F_{1\rightarrow 2} = \frac{1}{A_1}\int_{A_1}\int_{A_2} \frac{\cos\theta_1 \cos\theta_2}{\pi s^2}\, \mathrm{d}A_2\, \mathrm{d}A_1 \qquad (2)$$

of the 4 modules shown in Figure 3 at 40 sun positions requires one minute.



The cell level view factor model is capable of estimating the potential for mismatch among the cells on the back of the modules resulting from cell-to-cell variation in irradiance. Figure 5 illustrates a results from the cell level view factor model for the array depicted in Figure 3 using modeled clear sky direct and diffuse irradiance. At solar noon we observe variation of 10% or greater across each module as well as similar variation among modules. Cells at the array's edges receive more light than cells towards the array's center due to the wider view from these cells to sunlit areas behind the array. The effect on power of mismatch due to the irradiance variation is of significant interest to performance modelers.

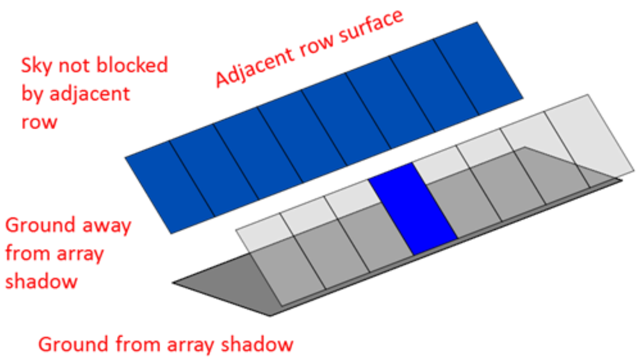


Fig. 4. Irradiance components considered in the detailed view factor model.

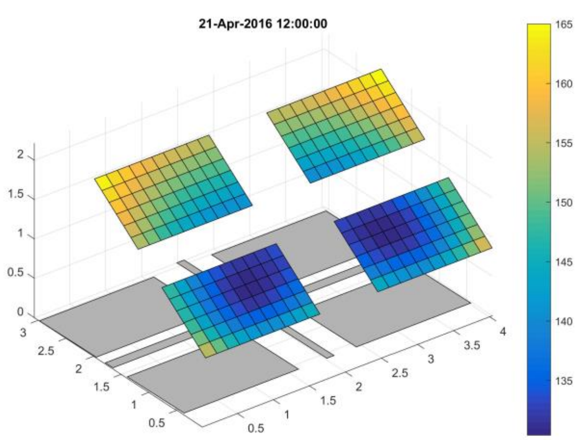
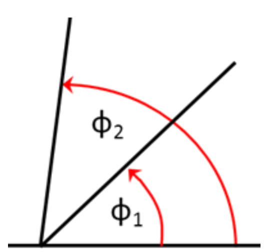


Fig. 5. Variation in back surface irradiance across a single row of modules at fixed tilt and solar noon.

The detail in the cell level view factor model may not be necessary to estimate performance of large, regular fixed rack arrays mounting bifacial modules. For these arrays a two dimensional array-scale model which neglects edge effects may be appropriate to estimate overall energy production. Figure 6 illustrates the components of irradiance considered in the array scale model View factors in the array scale model are given by a simple analytic expression (Eq. 3):

$$VF = 0.5(\cos\varphi_1 - \cos\varphi_2) \quad (3)$$



The array scale model could be implemented to estimate variation in back surface irradiance along the vertical dimension of a module, but not along its lateral dimension.

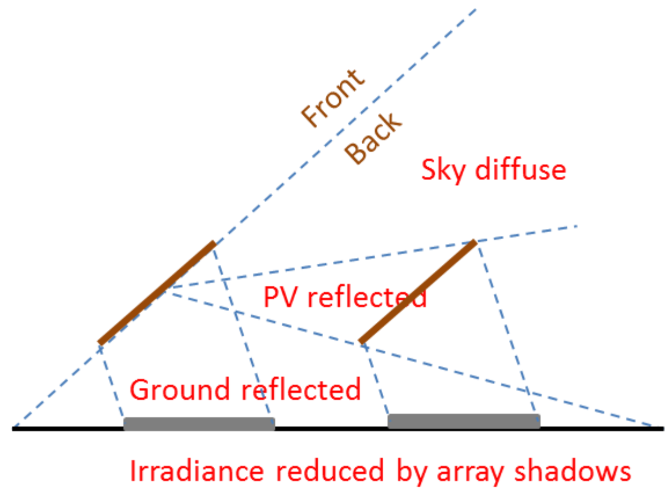


Fig. 6. Irradiance components considered in the 2D geometric model.

II.B Ray Tracing Simulations

Ray tracing models simulate the propagation of electromagnetic waves propagation 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.

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 simulated the array shown in Figure 3 using the open source software RADIANCE [4] and also the ray optics module of COMSOL. RADIANCE estimates the distribution of diffuse irradiance across the sky dome using the Perez model [5] and has been used previously for the modeling of bifacial PV installations [6]. For our application, we developed custom sky diffuse and ground reflected irradiance code for COMSOL. Both packages can provide physically realistic image rendering and illuminance mapping. RADIANCE uses backward ray tracing which is more efficient computationally for our application than forward ray tracing used by COMSOL. 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.

IV. Analysis

We applied the cell-level view factor model, RADIANCE and COMSOL to the array depicted in Figure 3 using measured

GHI and DNI on April 21, 2016 in Albuquerque NM. Irradiance instruments are located on a 3m weather platform approximated 50m to the east of the array. DHI is calculated from GHI, DNI and sun elevation. The cell-level view factor and RADIANCE calculations model sky diffuse irradiance using the Perez model [5] while COMSOL calculations are done with an isotropic sky diffuse model. For the cell-level view factor model we simulated back surface irradiance at 5 minute intervals completing 130 scenes in approximated 1 minute. RADIANCE simulations every 15 minutes (37 scenes) required several hours, as did three COMSOL scenes (at 10am, noon and 2pm). We believe these computation times to be typical of each type of model (view factor, backward ray tracing, and forward ray tracing). We did not apply the array scale view factor model to this array because the array's size is insufficient to provide a reasonable evaluation of the array scale model's 2D assumption of a 2D geometry.

We first examine front surface irradiance to judge if the different simulation results are biased by greater or lesser irradiance on the array. Figure 7 shows the plane-of-array (POA) irradiance averaged across the front of the lower right bifacial module. Except for two brief departures in the afternoon, both models follow the trends in the measured irradiance from the reference cells which evince clear sky conditions throughout the day. The GHI and DNI data show the departures correlate with brief shadow events that affect the meteorology instruments but not the array.

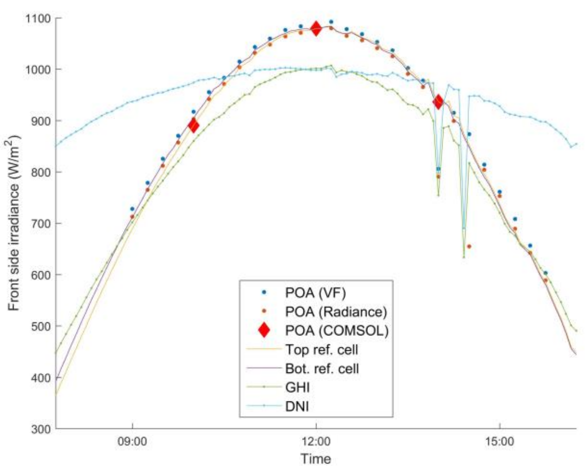


Fig. 7. Front surface irradiance on the lower right module for each simulation.

A bias towards lower front surface irradiance of approximately 5% is evident in the RADIANCE simulations compared to the cell-level view factor model. It is possible that the bias results from different albedo values in use (RADIANCE can model spatially varying ground albedo and a value of 0.1 is used for the asphalt surrounding the concrete pad, whereas the cell level view factor model uses a constant albedo of 0.2 for the ground surface). Another possible explanation for the bias is that RADIANCE models only three wavelengths and then estimates broadband irradiance by a scaled translation function.

Figure 8 displays the variation in irradiance across the back surface of the lower right module at noon. Contrary to the front surface irradiance comparison, the RADIANCE results are consistently higher than the view factor model results. The consistent difference between corresponding cells indicates a systematic discrepancy and provides hope that the two models may be brought into agreement by parameter adjustments. In contrast, the COMSOL results generally agree with the view factor model but the lack of smoothness in the COMSOL results indicates that the simulations may not yet be fully converged.

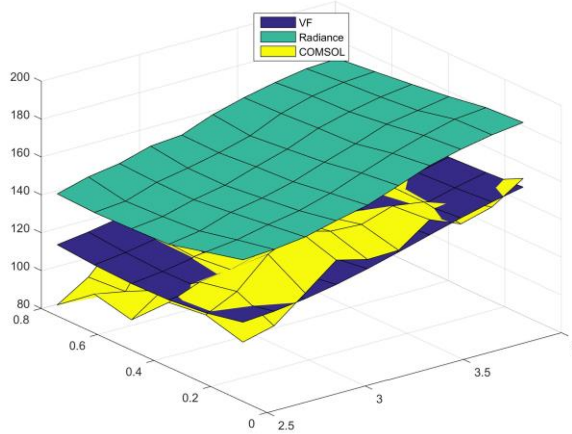


Fig. 8. Variation in irradiance on back surface of the lower right module at noon: grid points on cell centers.

Figure 9 compares simulated total irradiance (sum of front surface and back surface irradiance) to measured short circuit current (Isc) for the lower right module. The bifacial module exhibits a reasonably linear response to total irradiance. A line fitted to the data shows a lower slope for the RADIANCE simulation than from the view factor model corresponding to the bias in front surface irradiance. Hysteresis is evident in the data, with points corresponding to times before noon falling below and to the right of the fitted lines, and points at times after noon lying above and to the left. The hysteresis may result from a small rotation of the array's azimuth towards west of south and/or variation in module current due to changes in irradiance spectrum (precipitable water tends to systematically increase throughout the day in Albuquerque, NM). Figure 10 shows residuals for the fitted lines, confirming the systematic variation away from a line of the relationship between total irradiance and current from morning to afternoon.

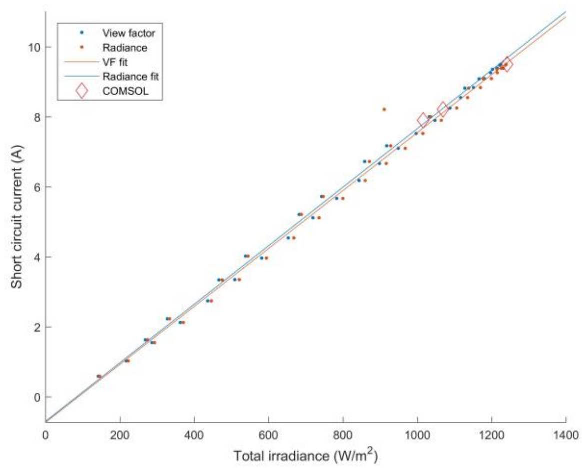


Fig. 9. Comparison between total irradiance and short circuit current for the lower right module.

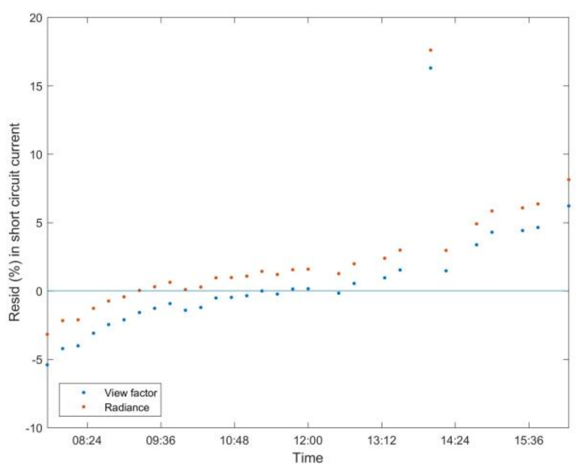


Fig. 10. Residuals in short circuit current for the lower right module from the line fitted to total irradiance.

IV. Discussion

Modeling of irradiance on bifacial PV modules may be done for a variety of purposes: to evaluate module design and materials, to analyze module performance outdoors, and to predict power production for arrays of bifacial modules. Our examination of view factor and ray tracing models illustrates that ray tracing models are likely suitable for aiding with module design and optimization because such models can faithfully represent details at levels which are impractical for view factor models. In contrast, ray tracing models are likely impractical for simulating array performance due to computational requirements. The cell level view factor model is suitable for small arrays, but because the computation time scales with the number of cells in the array, may not be practical for large arrays without careful management of the calculation. For modeling energy production from large arrays only the 2D array scale view factor model appears computationally feasible but as yet we do not have data (i.e., measured array current) with which to validate the model.

Results from the cell level view factor and ray tracing models agree surprisingly well with the measured irradiance and Isc, and among the models, given the limited effort applied to represent the four module array and the surrounding features. Differences between models and measurement are generally systematic, providing hope that parameter adjustments can lead to close agreement among models and between model results and data. Modeled irradiances correlates with measured Isc to within 5%, greater error than is typical for other performance models but not large enough to discourage model development and calibration.

Future work with these models will involve collecting data for the four module array at different tilt angles and heights above ground in order to explore and validate models for bifacial array performance over a wide range of geometries. The relative contribution to Isc of each component of total irradiance (sky diffuse, ground reflected, structure reflected) will be examined to enable evaluation of different modeling assumptions and to guide model development. Additional data will be collected for larger arrays comprising 20 or more modules in fixed racking at different orientations in order to evaluate and compare view factor models with different levels of detail.

Acknowledgements

This work was supported by the U.S. Department of Energy SunShot Initiative. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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