



A Practical Irradiance Model for Bifacial PV Modules

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Introduction

- Bifacial PV modules use radiation received by both the front and back surfaces, but only irradiance models for the front surface are fully developed and validated.
- This work developed a backside irradiance model and compared model estimates with backside irradiance measurements using reference cells installed on the backside of PV systems at NREL and Sandia.

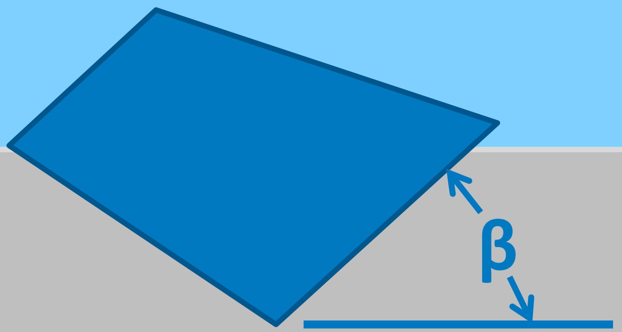
Model Overview

- Similar to models for the front side, configuration factors (*CFs*) are used. (The fraction of irradiance received from a source).
- Irradiance received by ground corrected for shadows and restricted view of the sky using array geometry.
- Irradiance corrected for AOI (beam & diffuse).
- Irradiances calculated for each row of cells in panel.
- Edge effects not considered.

Front Side Sky and Ground-Reflected Irradiance

$$I_{sky} = \text{DHI} \cdot (1 + \cos\beta)/2$$

CF

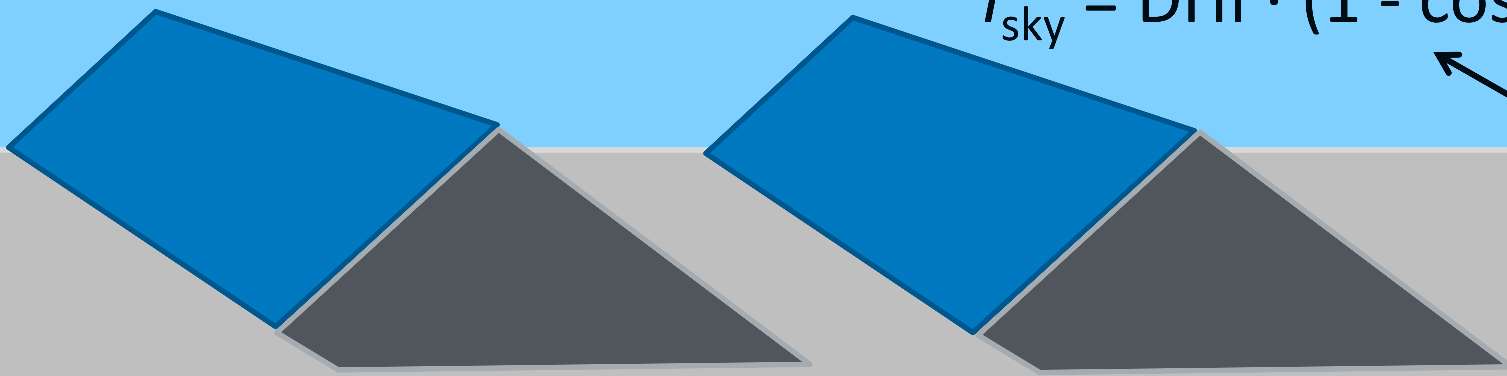


$$I_r = \rho \cdot \text{GHI} \cdot (1 - \cos\beta)/2$$

CF

Backside Sky and Ground-Reflected Irradiance

- *CF*s may also be used for the backside
- But only if the irradiance is the same intensity over the field-of-view



$$I_{sky} = \text{DHI} \cdot (1 - \cos \beta)/2$$

CF

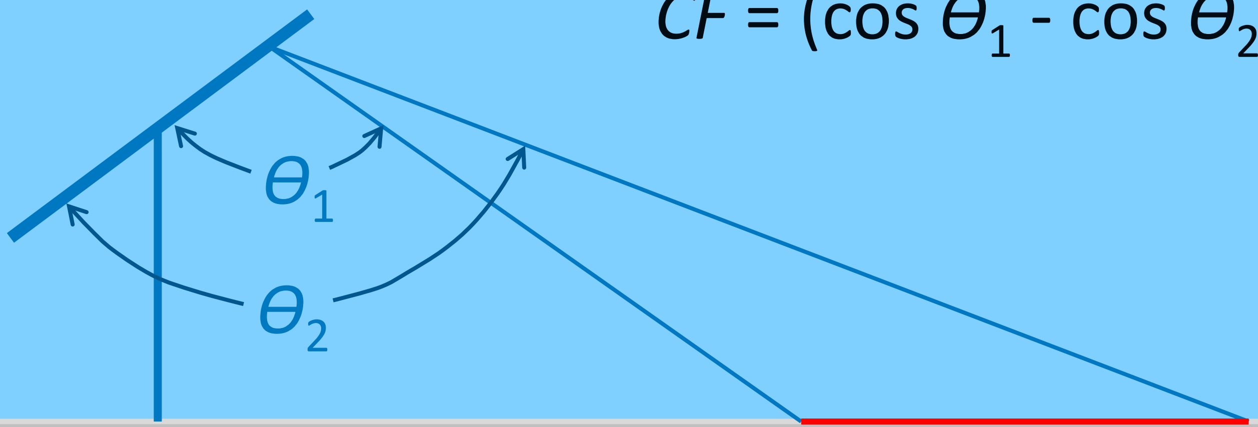
$$I_r = \rho \cdot \text{GHI} \cdot (1 + \cos \beta)/2$$

CF

CFs Using Field-of-View Angles

- Permits determining the contribution of each source of irradiance (shaded or unshaded ground, module reflections, etc.)

$$CF = (\cos \theta_1 - \cos \theta_2)/2$$



Irradiance Received by Ground Varies with Location

- Ground irradiance (GRI) is reduced by shadows and by the array reducing the view of sky
- Calculated at 100 locations in the row-to-row dimension

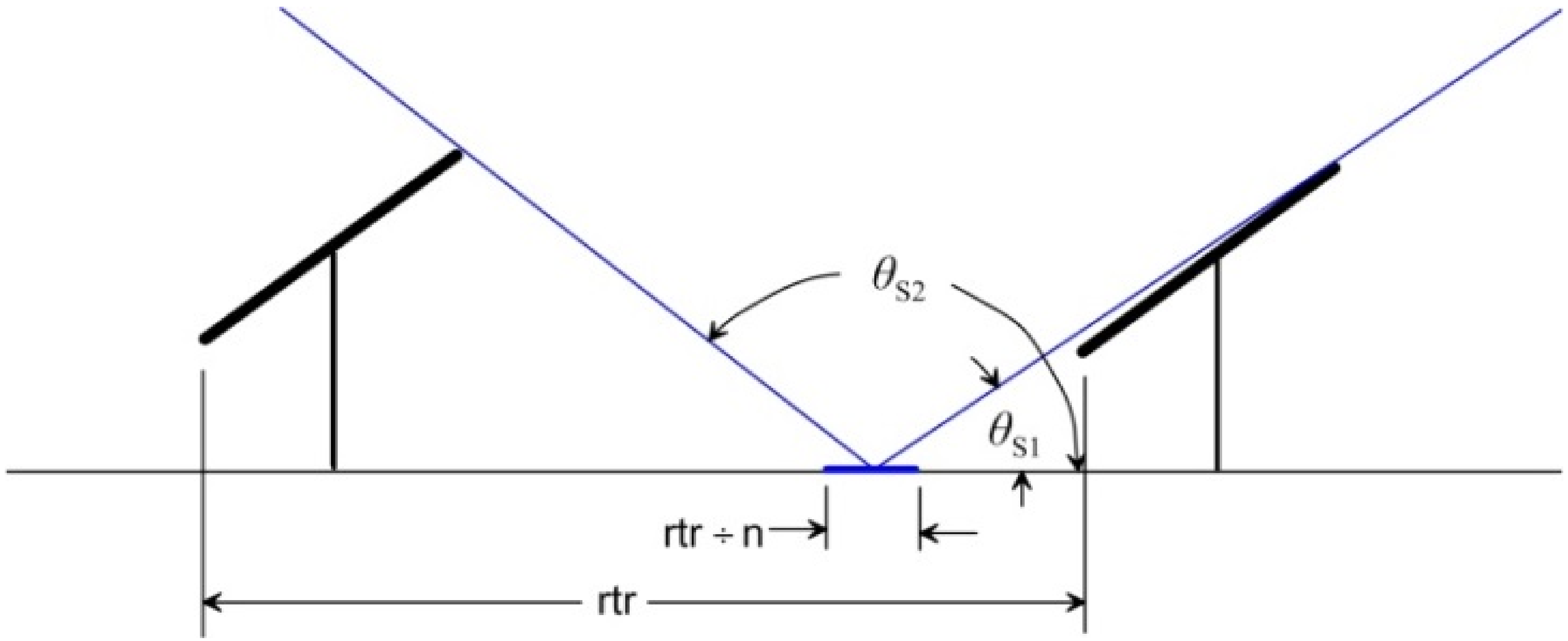
$$GRI = a \cdot (DNI + I_{cir}) + CF_{sky} \cdot I_{sky}$$

where:

a is the cosine of the sun zenith angle if the ground segment is unshaded. If shaded, *a* is the cosine of the sun zenith angle multiplied by the fractional opening of the PV array due to gaps between PV cells and modules.

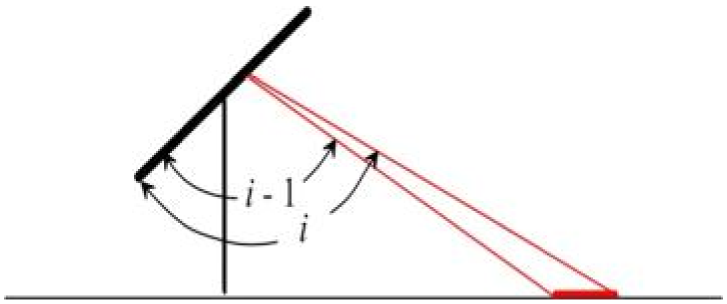
CF_{sky} Depends on Location in Row-to-Row Dimension

$$CF_{sky} = (\cos \Theta_{S1} - \cos \Theta_{S2})/2$$



Calculating the Backside Irradiance (BSI)

- Summed over 180° field-of-view using one degree increments



$$\mathrm{BSI} = b \cdot F_b \cdot (\mathrm{DNI} + I_{cir}) + \sum_{i=1°}^{180°} CF_i \cdot F_i \cdot I_i$$

where *b* = maximum (0, cosine of the AOI of the DNI); F_b and F_i are AOI corrections for the beam and diffuse[1]; and I_i is the irradiance viewed by the *i*th one-degree segment (either I_{sky}, I_{hor}, $\rho \cdot GRI_n$, or I_{refl}).

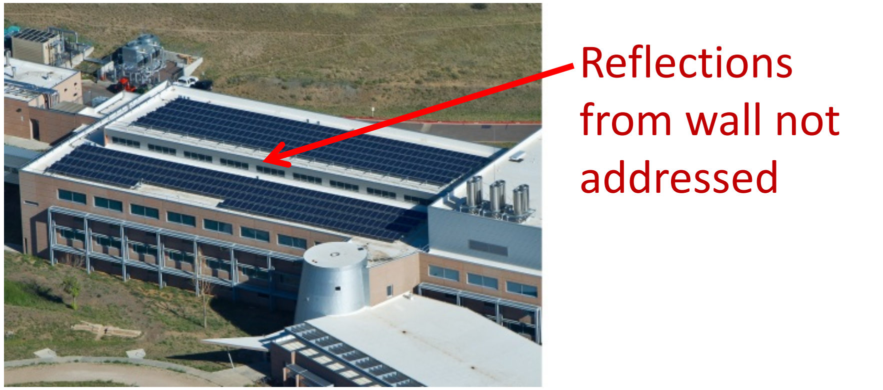
[1]B. Marion, "Numerical method for angle-of-incidence correction factors for diffuse radiation incident photovoltaic modules", *Solar Energy* 147: 344–348, 2017.

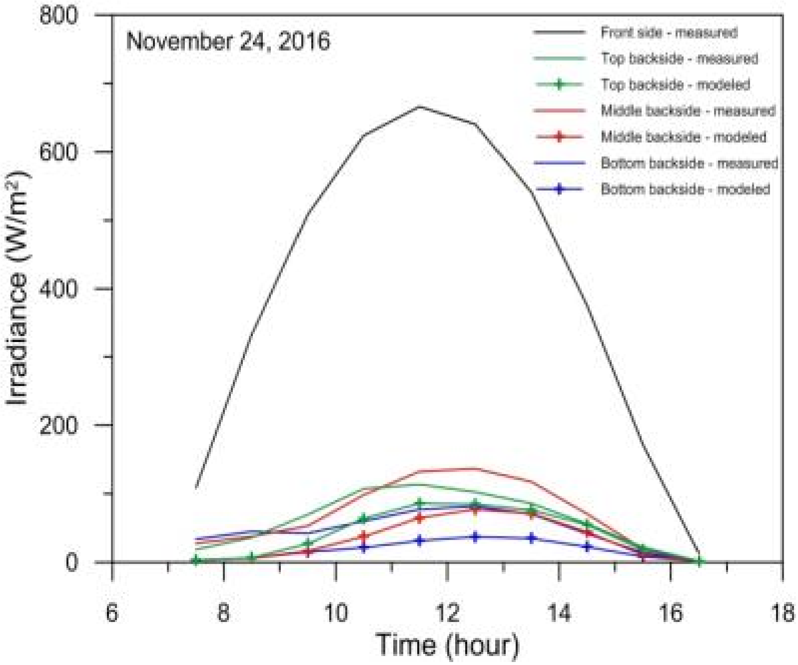
Validation Data

- Model Input – Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI), used with Perez model to derive circumsolar, sky, and horizon diffuse.
- Measured backside irradiances for NREL and Sandia systems.

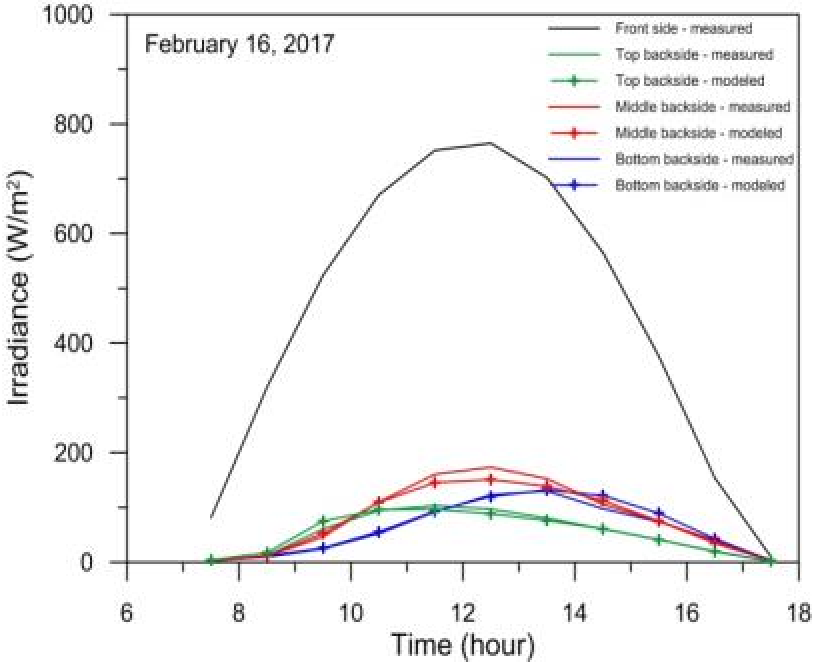
Validation Results – NREL Site

- Better results for upper roof than for lower roof.
- Off south azimuth shifts BSI peak values.





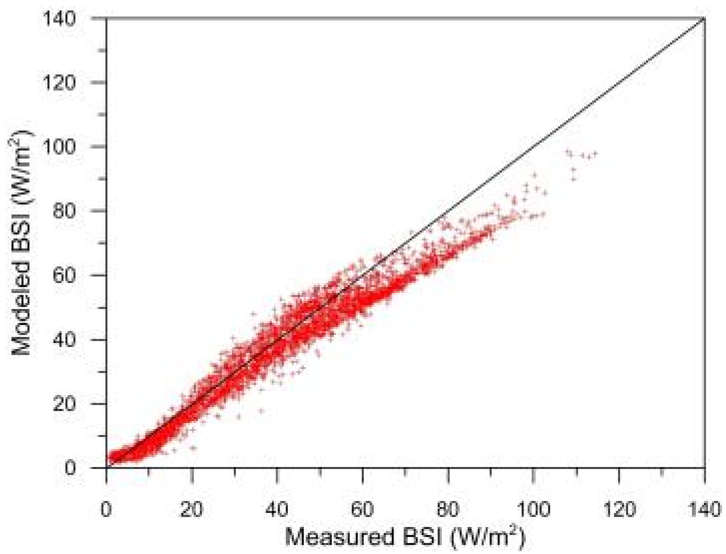
Lower Roof



Upper Roof

Validation Results – Sandia Site

- Data for 10/1/2016 thru 3/31/2017 – 15 minute averages.
- Mean for bottom reference cell was 10% of front side.
- Mean for top reference cell was 7% of front side.
- Model MBD ranged from -4 to 9 W/m^2, -9 to 16%.
- Model RMSD ranged from 5 to 16 W/m^2, 14 to 31%.

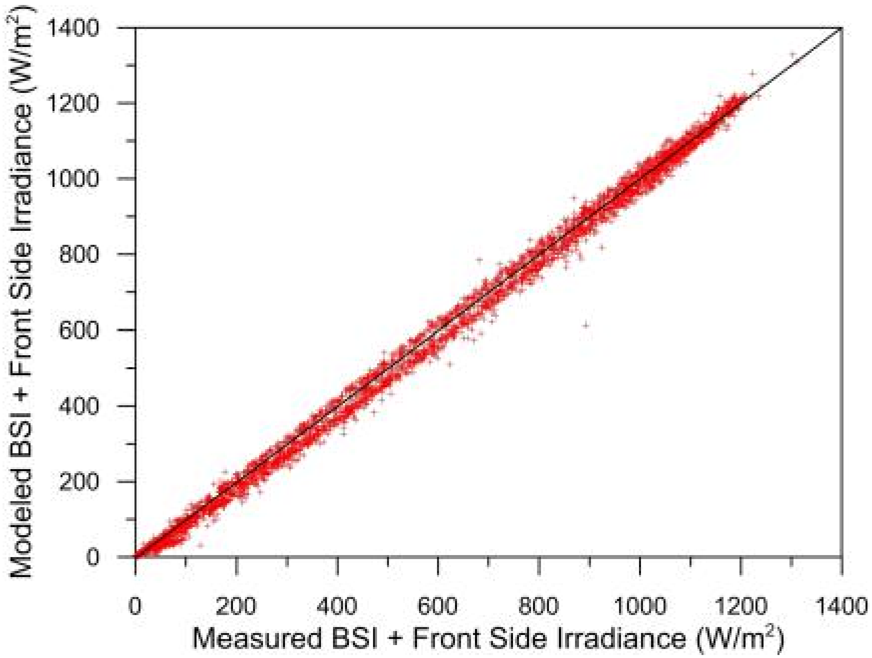


Modeled Versus Measured BSI for Top Reference Cell in 35° Tilt Row

Validation Results – Sandia Site (continued)

BSI plus front side irradiance – total irradiance to PV cell.

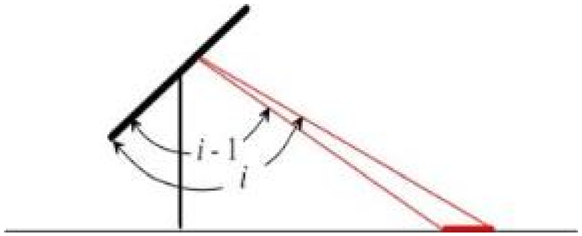
- Model MBD ranged from -11 to 14 W/m^2, -1.8 to 2.4%.
- Model RMSD ranged from 25 to 36 W/m^2, 4 to 6%.

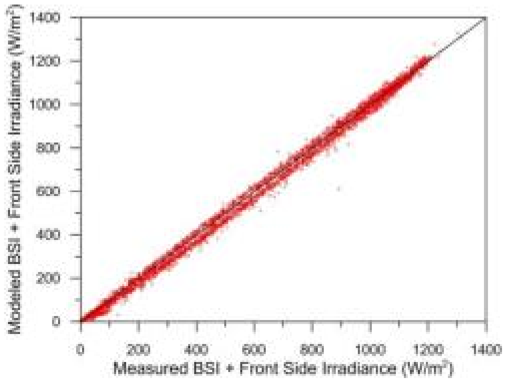


Modeled Versus Measured <u>BSI Plus Front Side Irradiance </u>for Top Location in 35° Tilt Row

Summary

- The backside irradiance model for bifacial PV systems uses configuration factors, and accounts of the effects of shading, restricted view of the sky, and angle-of-incidence for both beam and diffuse radiation.
- The model was validated using data from NREL and Sandia.
- The model MBD for the total irradiance available to the PV cell (BSI plus front side irradiance) was within ±2.5%.





Questions?

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