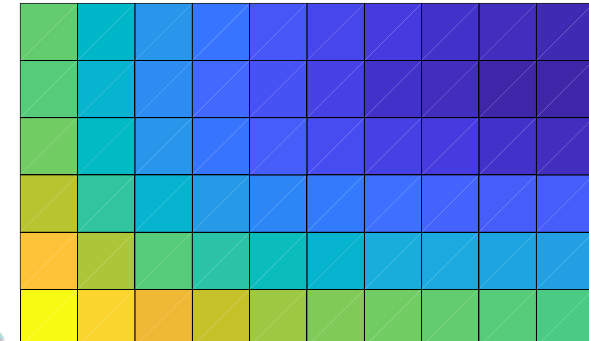
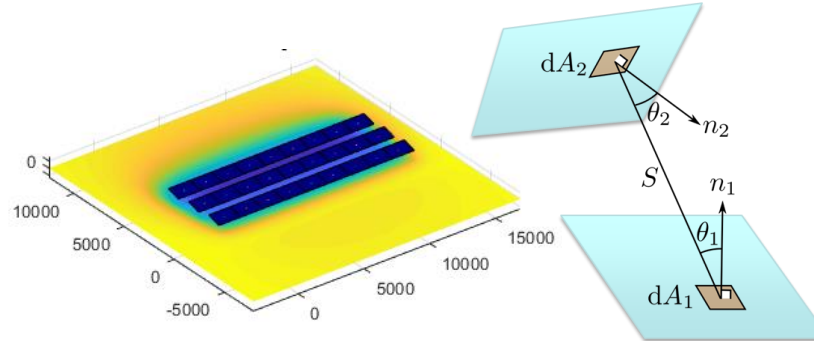
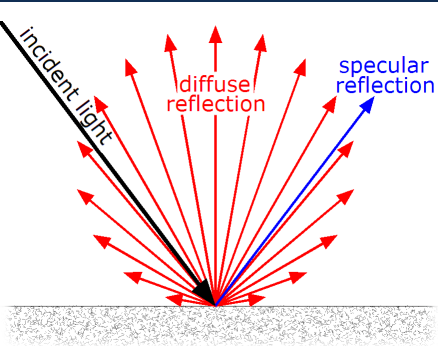


Exceptional service in the national interest



Comparison of modeling methods and tools for bifacial PV performance

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Bill Marion

Fatima Toor

Amir Asgharzadeh Shishavan

Sandia National Laboratories

National Renewable Energy Laboratory

University of Iowa

3-Yr Bifacial Research Project (2016-2018)

Collaborative project between Sandia, NREL and University of Iowa
(pvpmc.sandia.gov/pv-research/bifacial-pv-project/)

Task 1: Measure Outdoor Bifacial Performance

- Module scale
 - Adjustable rack IV curves (height, tilt, albedo, and backside shading effects)
 - Spatial variability in backside irradiance
 - Effects of backside obstructions
- String scale
 - Fixed tilt rack (tilt, mismatch effects)
 - Single axis tracker (investigate potential)
 - Two-axis tracker
- System scale
 - String level monitoring on commercial systems (validation data)



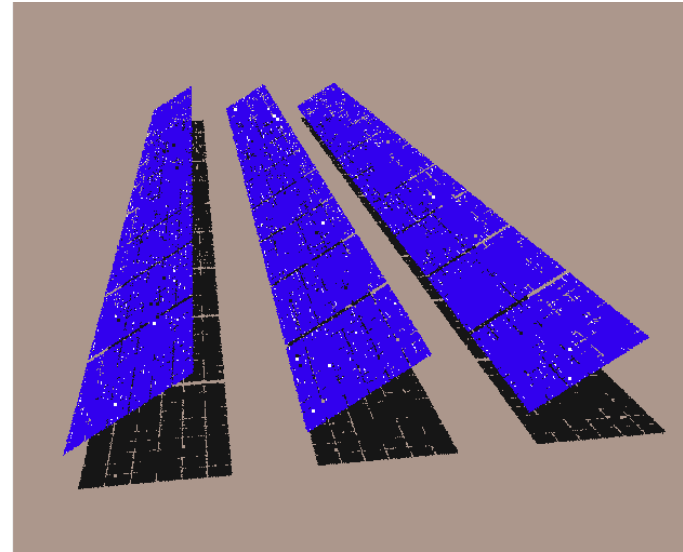
Stein, J. S., D. Riley, M. Lave, C. Deline, F. Toor and C. Hansen (2017). Outdoor Field Performance of Bifacial PV Modules and Systems. 33rd European PV Solar Energy Conference and Exhibition. Amsterdam, Netherlands. SAND2017-10254

3-Yr Bifacial Research Project (2016-2018)

Task 2: Develop Bifacial PV Performance Models

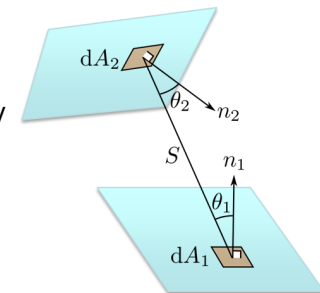
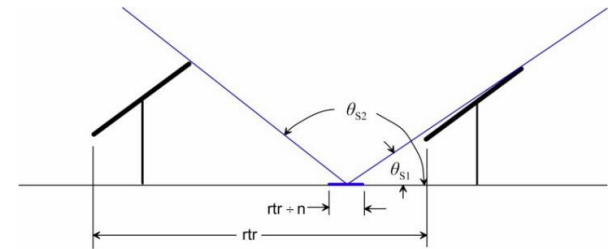
Ray Tracing simulation

- Bifacial_Radiance software release
 - github.com/cdeline/bifacial_radiance
 - CumulativeSky preprocessor
- Configuration analysis publication¹
 - Effect of row spacing, tilt optimization
 - Validation of model using Sandia field data
- CumulativeSky



View Factor models

- “2D” – BifacialVF software release²
 - github.com/cdeline/bifacialVF
- “3D” – Matlab code to be released soon on the PVPMC³.



¹ A. Asgharzadeh et al, “Analysis of the impact of installation parameters and system size on bifacial gain and energy yield of PV systems”, IEEE PVSC 2017

² B. Marion et al., “A Practical Irradiance Model for Bifacial PV Modules”, 44th IEEE PVSC 2017. Washington DC. <https://www.nrel.gov/docs/fy17osti/67847.pdf>

³ C. Hansen et al., “A Detailed Model of Rear-Side Irradiance for Bifacial PV Modules”. 44th IEEE PVSC 2017. Washington DC. SAND2017-6554 C.

Bifacial PV Performance Models

- Detailed formulations require front and backside irradiance maps, module temperature, angle of incidence, shading descriptions, etc.

- Simple bifacial performance is based on the calculation of *Bifacial Gain*

- $E_{bifacial} = (1 + BG_E) E_{monofacial}$

- *Bifacial Energy Gain* (BG_E) = *Bifaciality* * *Rear Irradiance Ratio* – *Mismatch loss*

- » *Bifaciality* = $\frac{P_{mp, rear}}{P_{mp, front}}$ (from single side flash data)*

- » *Rear Irradiance Ratio* = $f(\text{albedo, tilt, row spacing, height, diffuse ratio, sun position, position in row, etc.})$

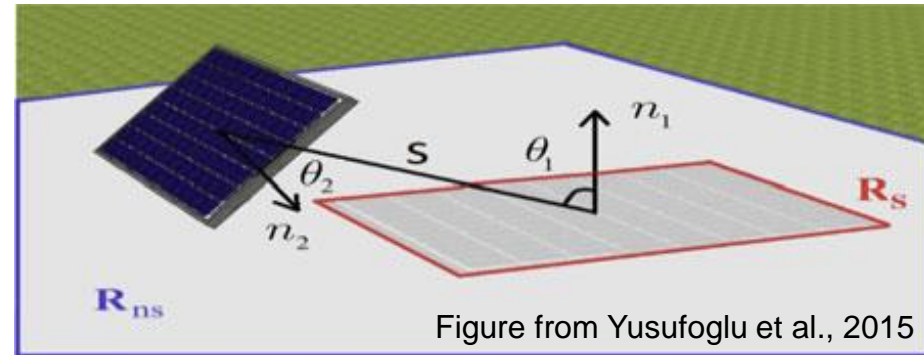
- » *Mismatch loss* is due to rear irradiance spatial variability, shading, racking, and electrical configuration (string vs. microinverter)

Bifaciality

- Bifacial modules have a range of bifaciality depending on cell technology and design.
 - N-type Silicon (e.g. Prism Solar) ~90%
 - Hetrojunction (e.g., Sanyo, Panasonic, SunPreme) ~90%
 - PERC (e.g., SolarWorld, Longi Solar) ~60-75%
 - IBC (e.g., SunPower) ~30%
- Caution: Increasing bifaciality can lead to decreases in frontside efficiency.

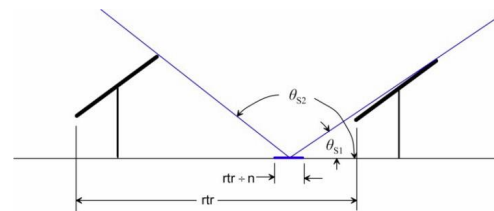
Rear Irradiance Ratio

- Rear Irradiance Ratio = $\frac{G_{rear}}{G_{front}}$
- G_{front} is calculated using conventional transposition models
 - e.g., Perez, Hay & Davies, etc.
- G_{rear} depends on many factors
 - Ground-reflected irradiance (albedo, tilt, height, row-spacing, position in row, Sun position)
 - Sunlit ground
 - Shaded ground
 - Sky-diffuse irradiance (tilt, row-spacing, sun position)
 - Direct irradiance on back of array (tilt, azimuth, Sun position (season, latitude))

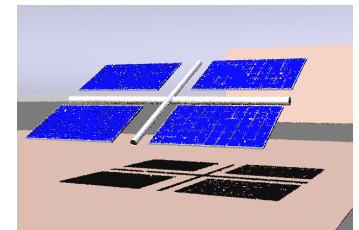


R_{ns} is unshaded ground
 R_s is shaded ground
 S is the distance from module/cell to shadow

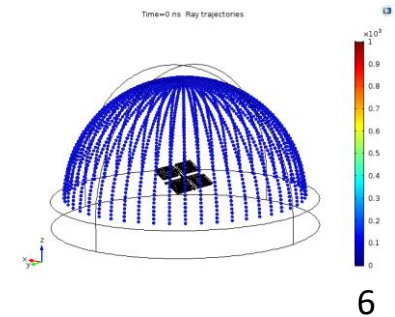
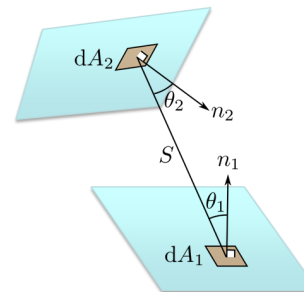
2D View Factor



3D Ray Trace



3D View Factor



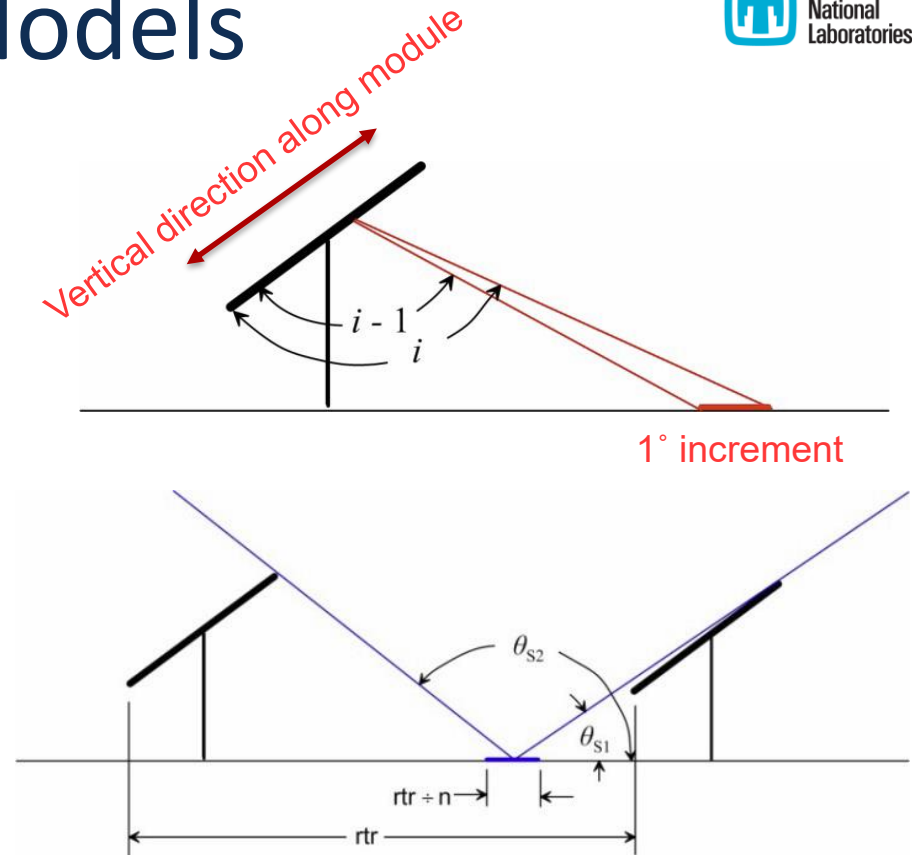
Measuring Rear Irradiance

- Sandia built a “mock” PV module with ten reference cells mounted on the backside.
 - Placed this “module” in different positions in arrays to measure the spatial irradiance patterns on the back of the array.
- NREL built a half-scale array model with three rows, adjustable tilt, height, and row-spacing.
 - Placed 4 reference cells facing back and 2 facing forwards in the middle of the middle row



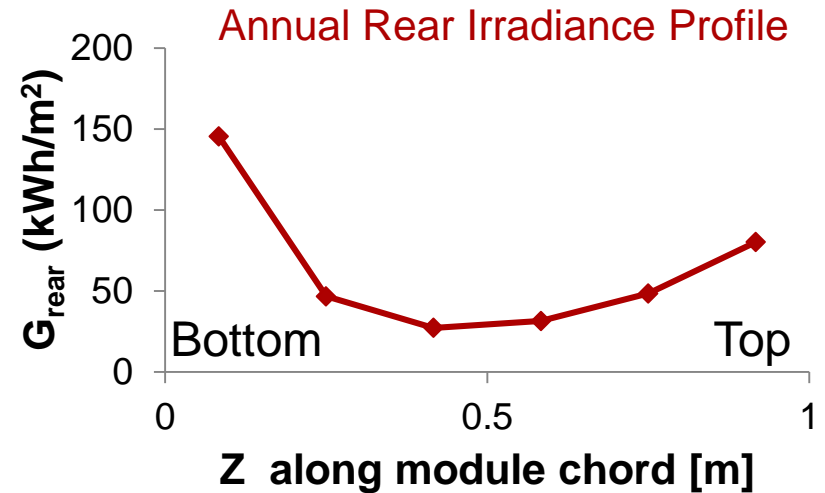
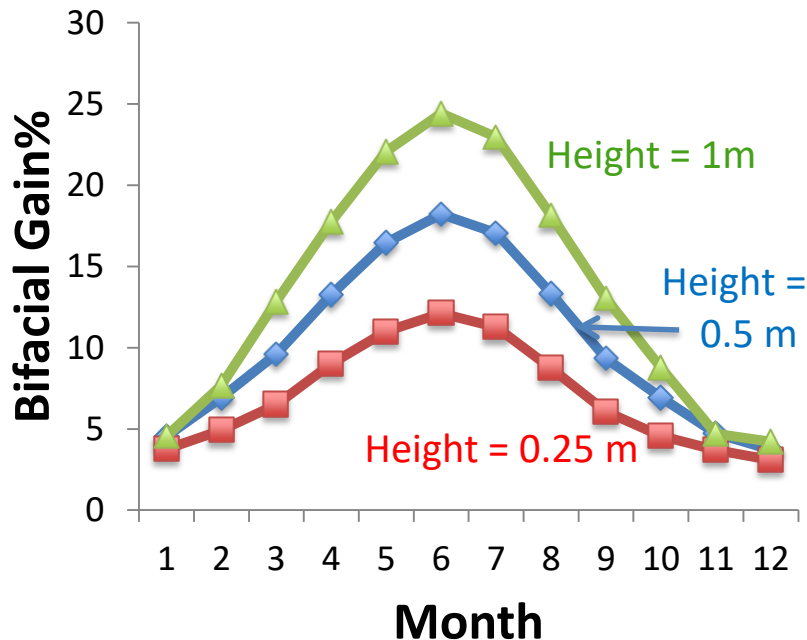
“2D” View Factor Models

- NREL model calculates backside irradiance for each row of cells and builds an irradiance profile along the “vertical” direction of the module or array.
- Backside irradiance at a point on the module is the sum of:
 - AOI corrected beam irradiance + $\sum_{i=1}^{180^\circ} VF_i F_i I_i$
 - VF_i = view factor for each increment
 - F_i = AOI correction
 - I_i = Irradiance viewed by the i^{th} increment
- Irradiance is either from sky diffuse, ground reflected, or reflected from other parts of the array (rows behind).
- PVsyst implements a similar approach.



Example “2D” VF Results

- Model provides irradiance along a vertical profile of the module or array



- Fast simulation time (within seconds) provides monthly trends or annual hourly results

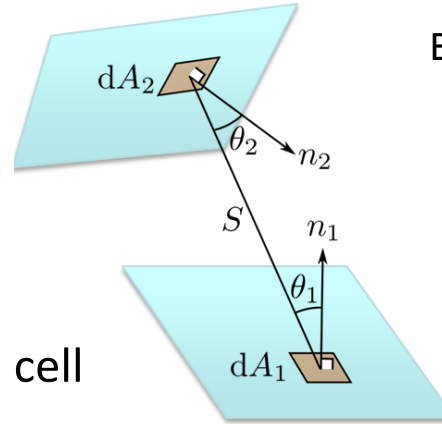
“3D” View Factor Model

- Sandia model is similar to 2D model except integration is performed over 2D ground grid and 3D objects.

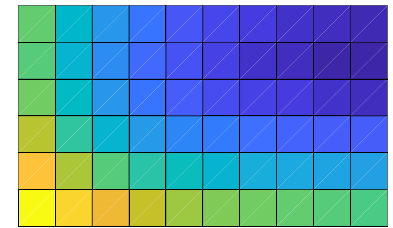
$$F_{1 \rightarrow 2} = \frac{1}{A_1} \int_{A_1} \int_{A_2} \frac{\cos \theta_1 \cos \theta_2}{\pi S^2} dA_2 dA_1$$

$$E_{back,k}(t) = E_{ground,k}(t) + E_{sky}(t)VF_{k \rightarrow sky} + E_{beam}(t)$$

$$E_{ground,k}(t) = \sum_i \alpha_i G_i(t) VF_{i \rightarrow k}$$

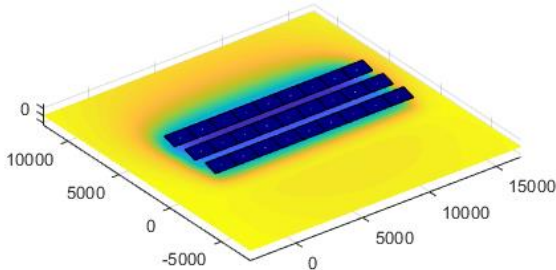


Backside irradiance map

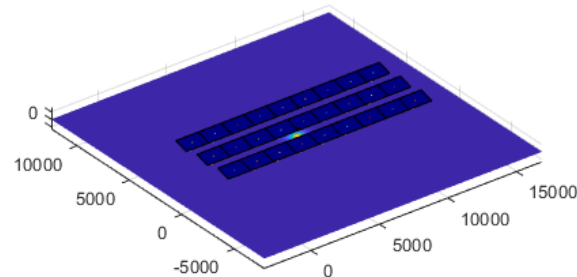


- Backside irradiance is calculated for each 2D cell
- Ground irradiance is calculated on a 2D grid
- Other modules and structures cast shadows on ground but do not directly reflect light to cells.

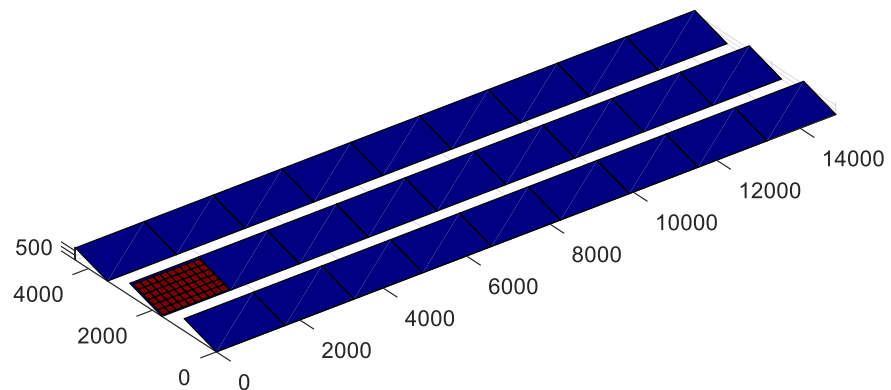
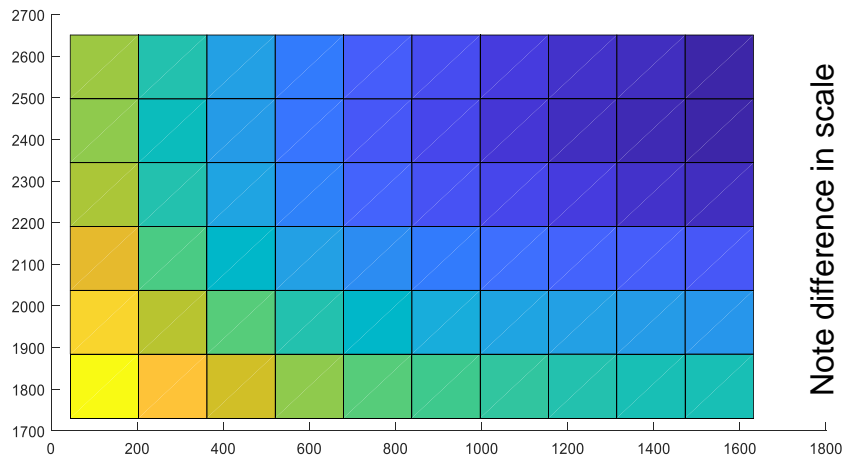
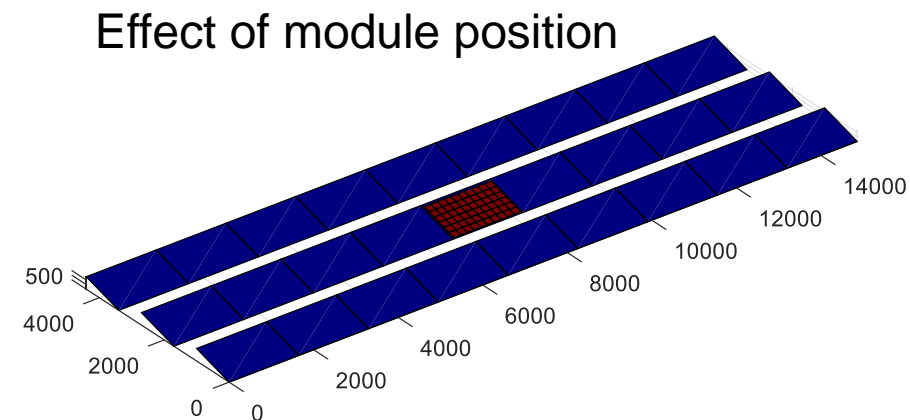
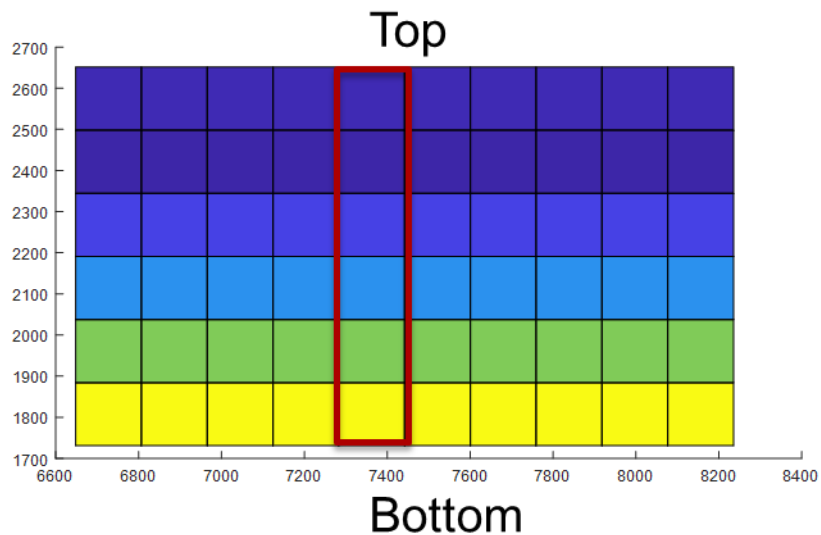
Ground to sky view factors



View factors for Row2 Pos5, Cell (1,1)



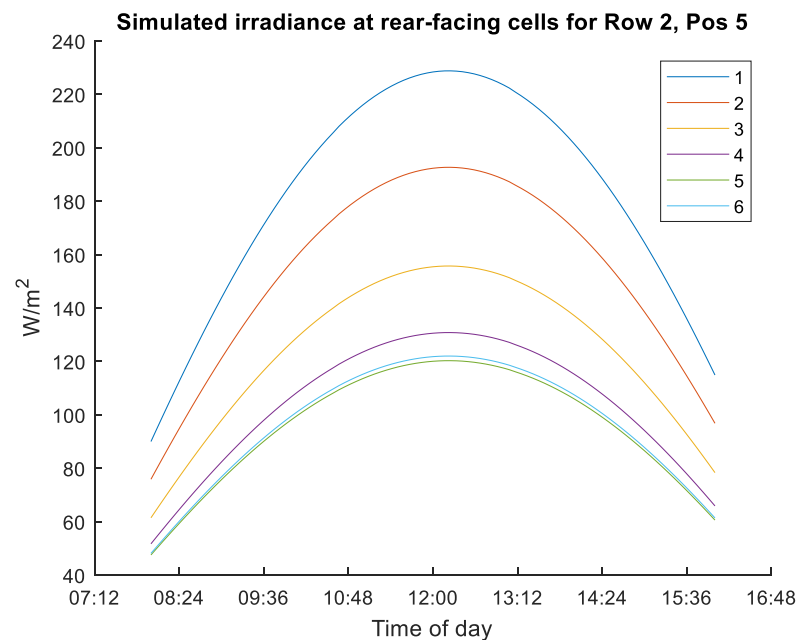
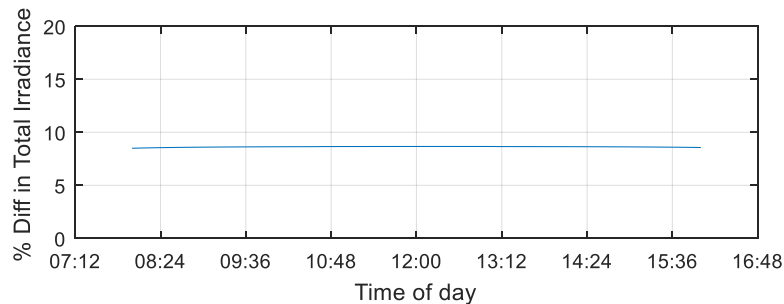
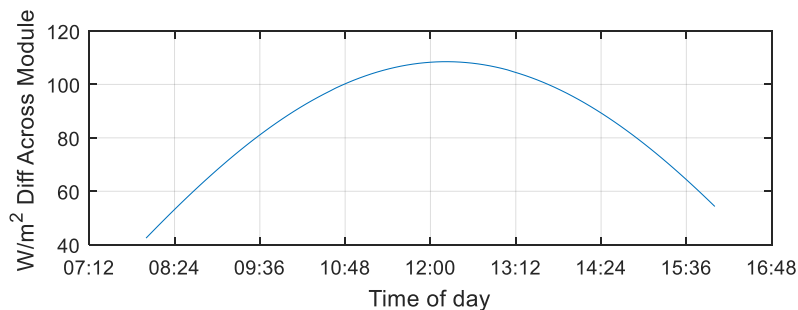
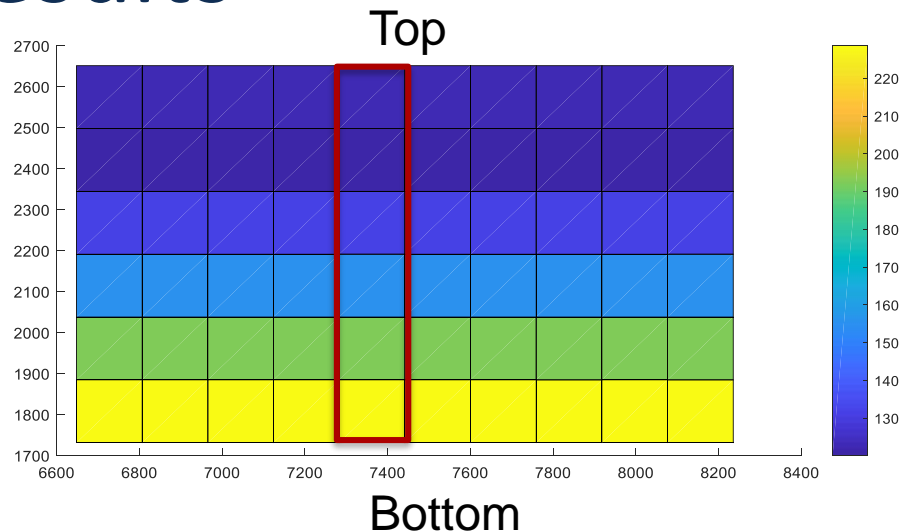
Example "3D" VF Results



Solar noon on the spring equinox.

Example “3D” VF Results

- Clear Sky, Spring equinox, Albuquerque, NM (35°N)
- 15 deg tilt
- Albedo = 0.55
- Height = 0.5 m
- Row spacing = 2 m



3D Ray Trace Model

- Based on RADIANCE (reverse ray tracing model from LBNL)
- Can include complex objects (racking, ballast, equipment racks, etc.)
- Computationally complex
 - Run times are slow
- 8760 hr annual simulations not practical unless....
 - CumulativeSky approach¹ integrates time varying irradiance into annual insolation.

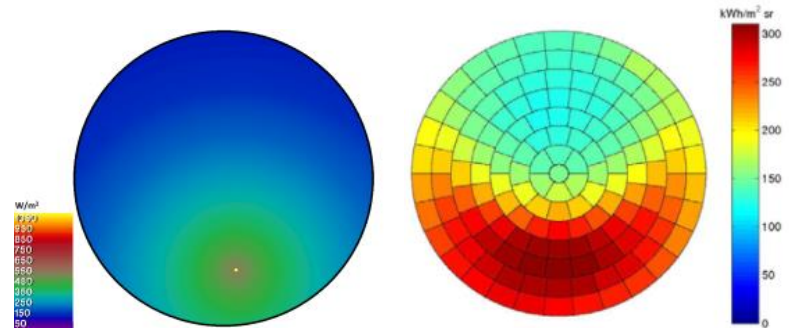
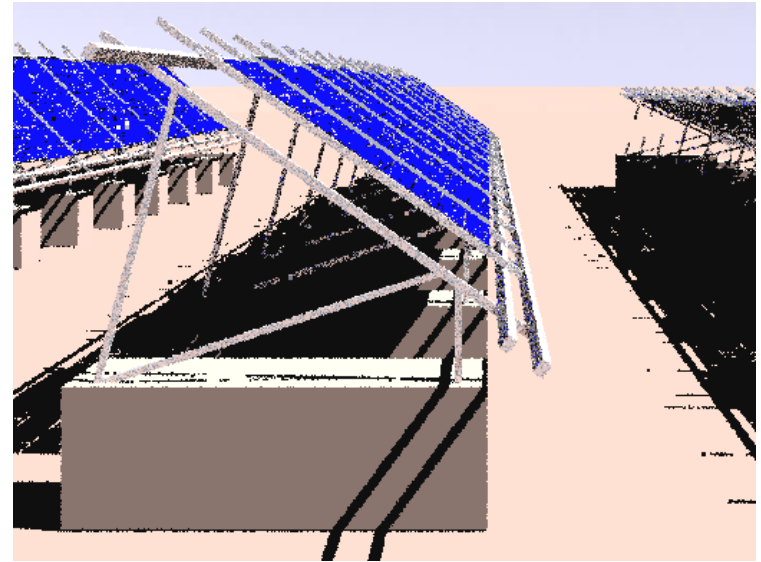


Figure 1 Cumulative diffuse sky radiance distribution for Oslo (based on 10yr mean solar data).

Single hourly
Perez sky (W/r)

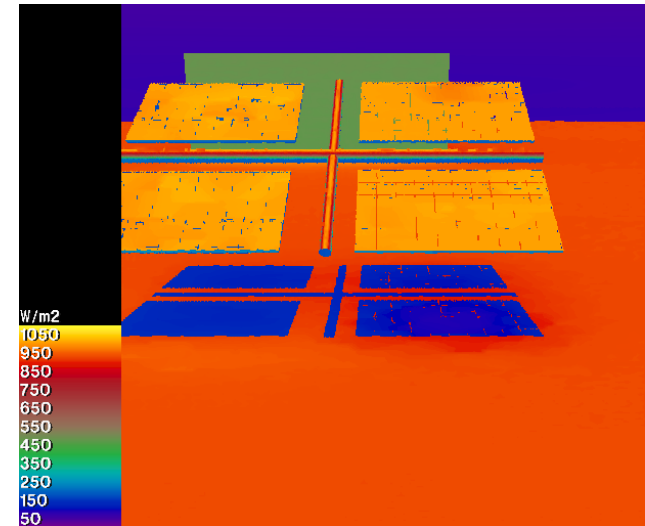
Annual cumulative sky
conditions (kWh/m²)

Example Ray Trace Results

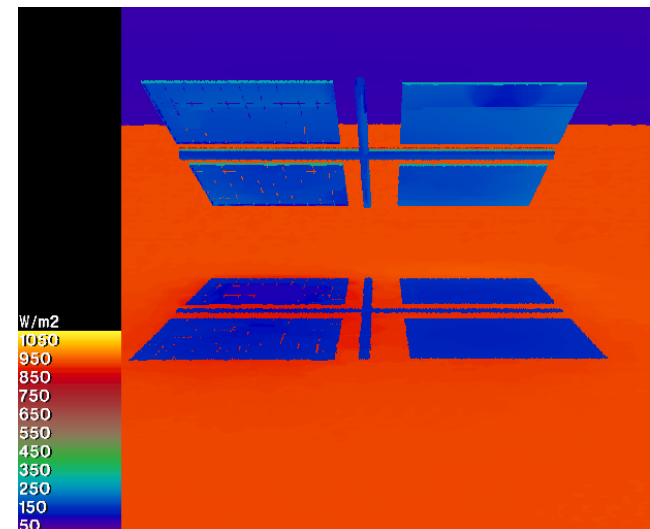
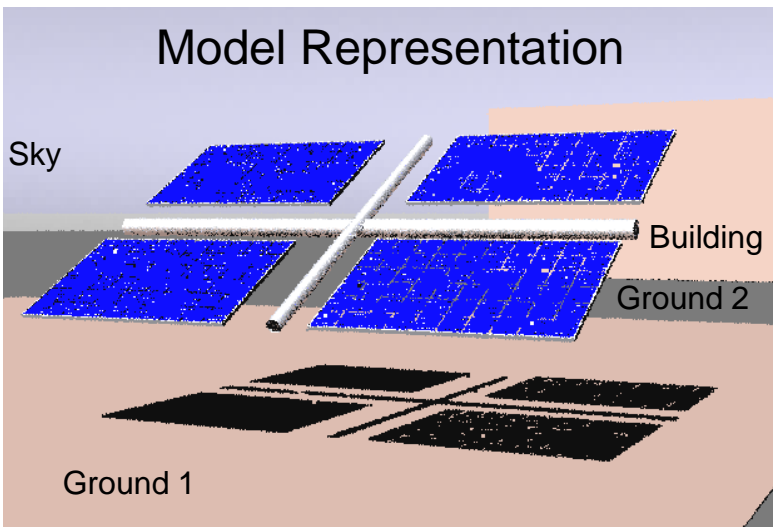
Real system



Irradiance Results

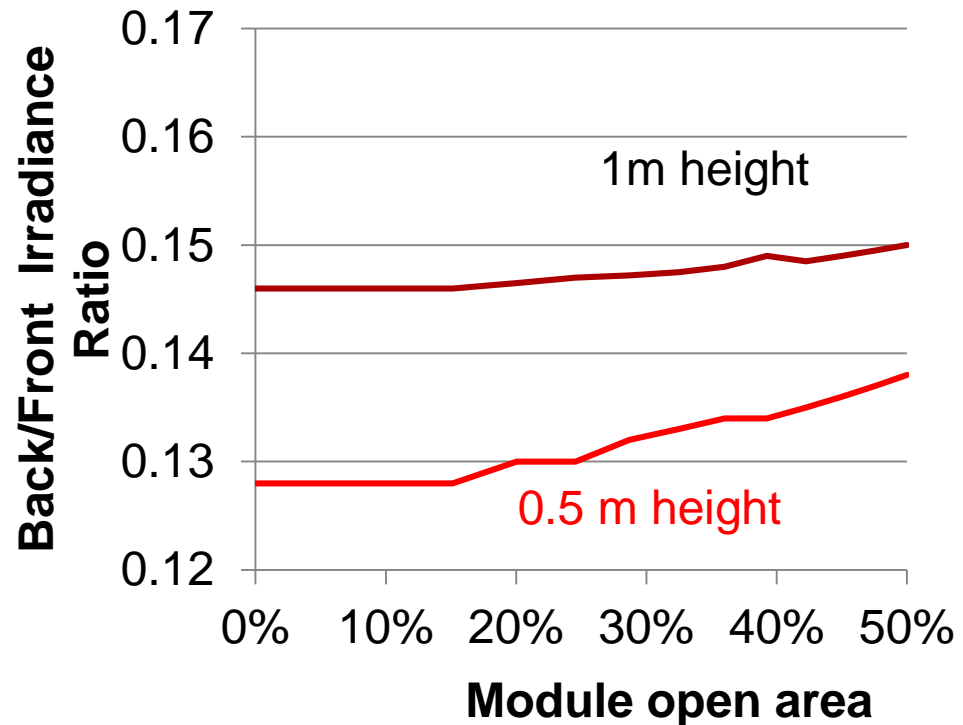
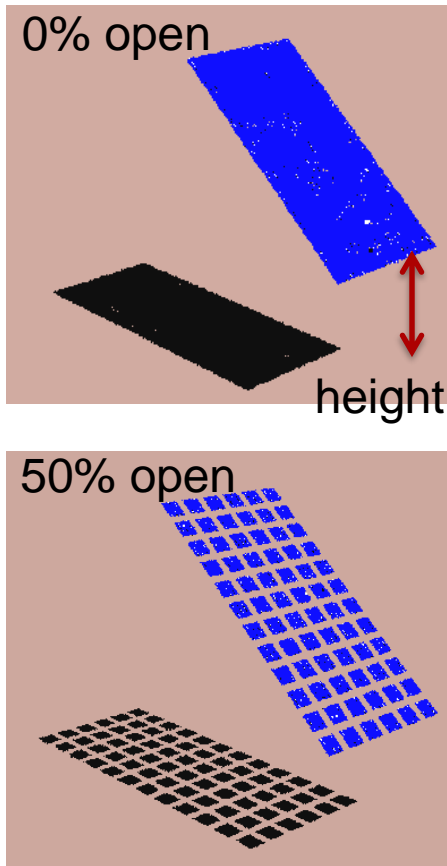


Model Representation



Example Ray Trace Results

Effect of height and cell spacing



Summary

- Modeling of bifacial performance is done for a variety of reasons
 1. Evaluate bifacial module and system designs (effects of frame, j-box, cell spacing, etc.).
 2. Analyze module or small system performance outdoors.
 3. Analyze bifacial system performance in large arrays.
- 2D view factor models are best for production estimates from large systems with uniform rows.
- 3D view factor model can simulate edge effects and small and diverse systems.
- 3D Ray tracing allows specific details to be included (e.g., frames, racking, ballast, inverters, combiners, BOS, etc.).

Questions?



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