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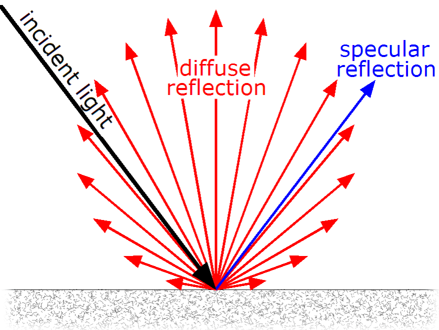

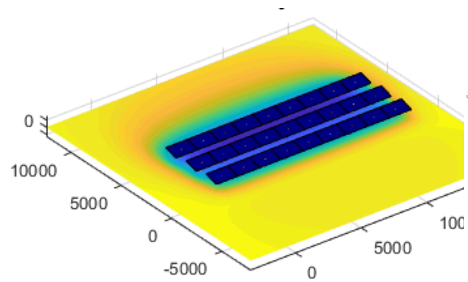

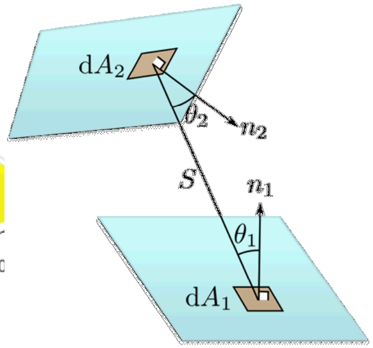

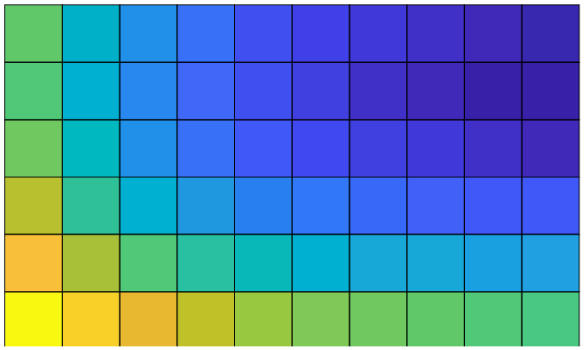

Comparison of modeling methods and tools for bifacial PV performance

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Clifford Hansen
Chris Deline National Renewable Energy Laboratory
Bill Marion
Fatima Toor University of Iowa
Amir Asgharzadeh Shishavan

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3-Yr Bifacial Research Project (2016-2018)

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

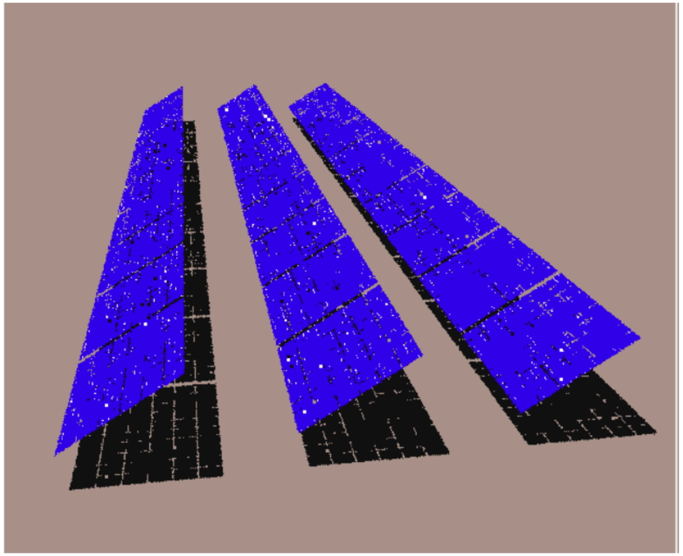
Task 1: Measure Outdoor Bifacial Performance

- 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

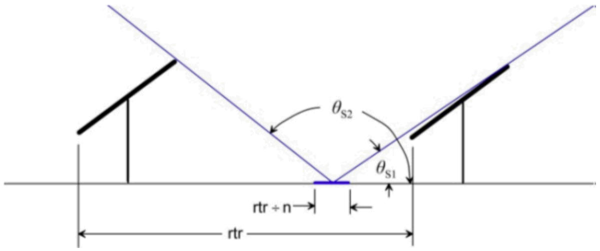


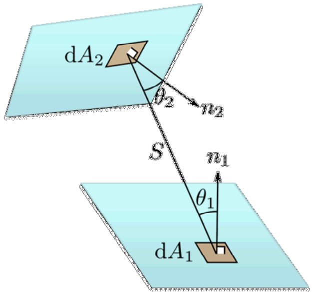
Ray Tracing simulation

- Bifacial_Radiance software release
  - **github.com/cdeline/bifacial_radiance**
  - CumulativeSky preprocessor
- Configuration analysis publication[1]
  - Effect of row spacing, tilt optimization
  - Validation of model using Sandia field data
- CumulativeSky

View Factor models

- "2D" – BifacialVF software release[2]
  - **github.com/cdeline/bifacialVF**
- "3D" –Matlab code to be released soon on the PVPMC [3].





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

* V. Fakhfouri IEC TS 60904-1-2 ED1 (2017)

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))

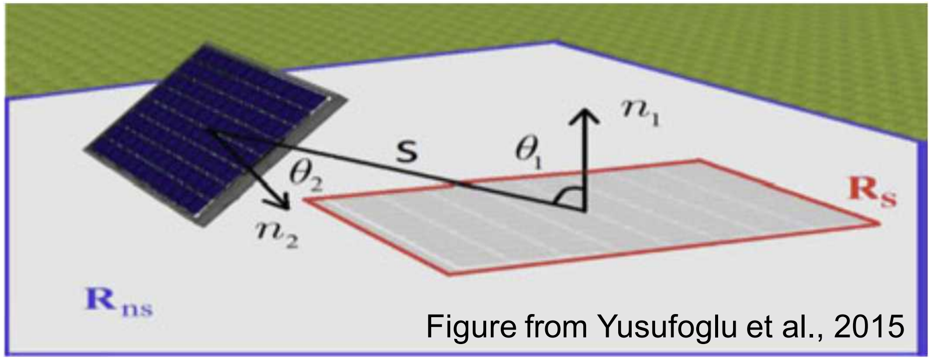
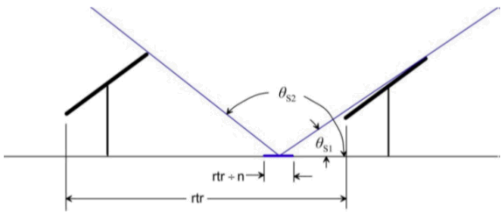


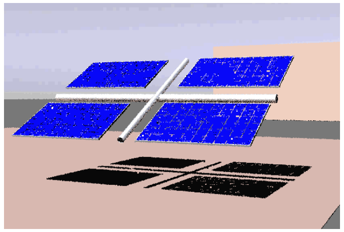
Figure from Yusufoglu et al., 2015

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

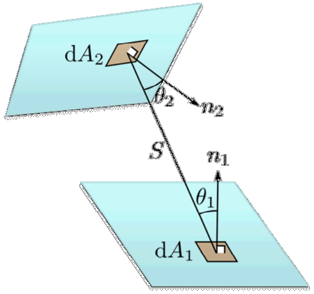
2D View Factor

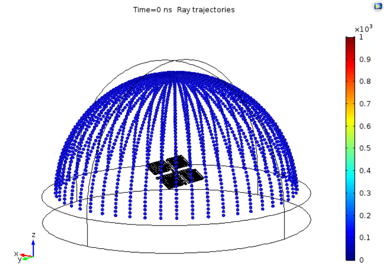


3D Ray Trace



3D View Factor





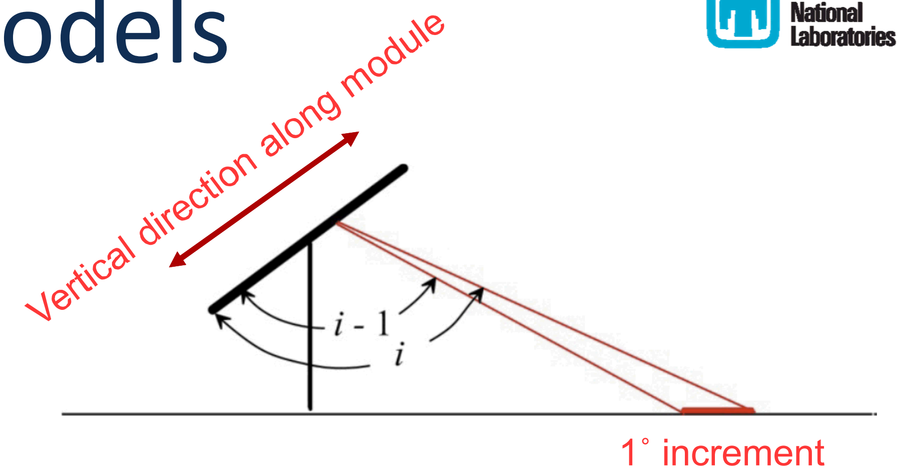
Measuring Rear Irradiance

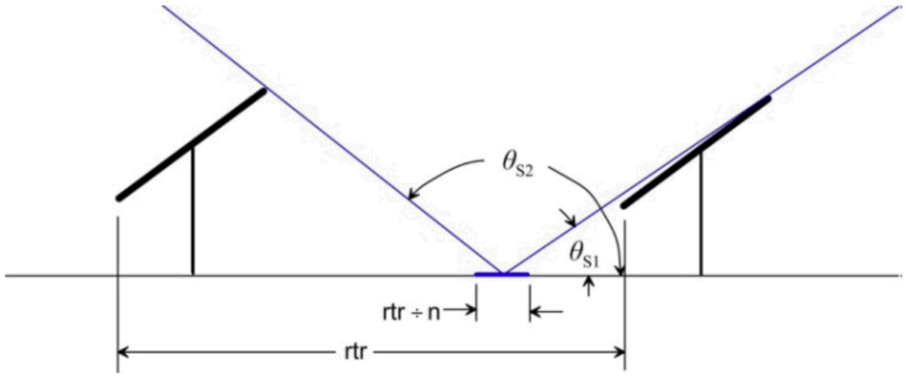
- Sandia built a “mock” PV module with ten reference cells mounted on the backside.
  - Placed this “module” in different positions in arrays to measure the spatial irradiance patterns on the back of the array.

- 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

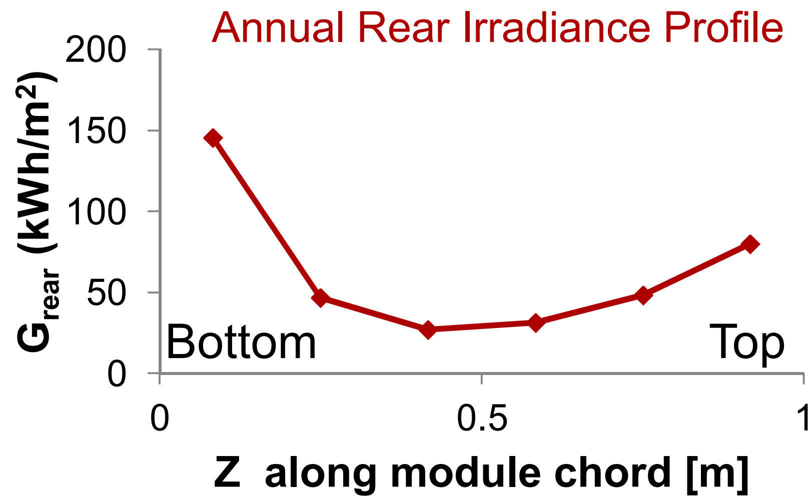
- NREL model calculates backside irradiance for each row of cells and builds an irradiance profile along the “vertical” direction of the module or array.
- Backside irradiance at a point on the module is the sum of:
  - AOI corrected beam irradiance + $\sum_{i=1^\circ}^{180^\circ} VF_i F_i I_i$
    - 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.

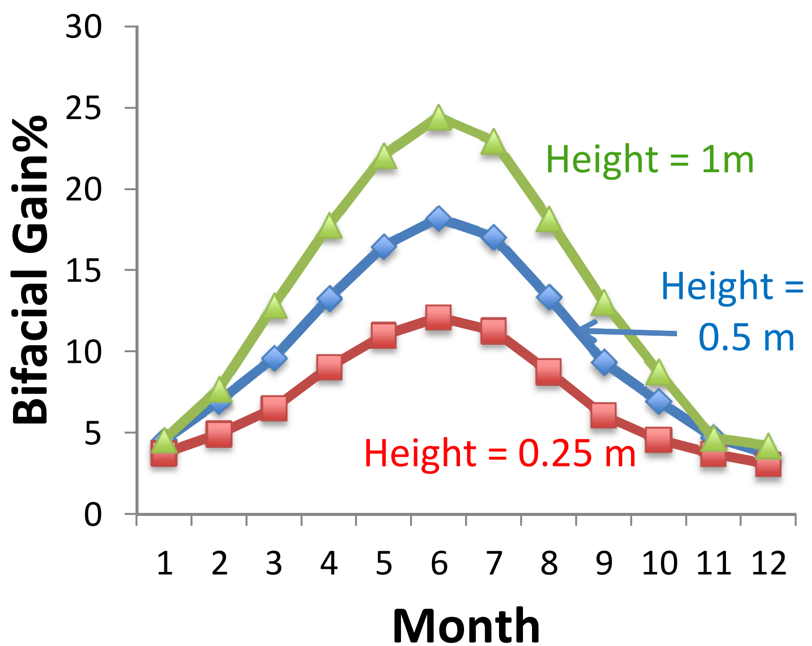




Example "2D" VF Results

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





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

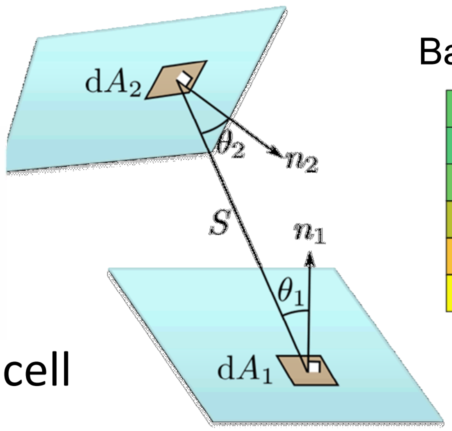
"3D" View Factor Model

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

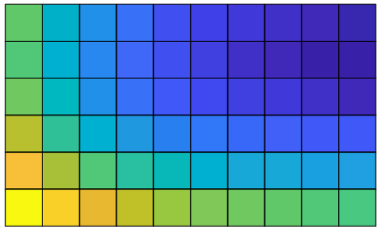
$$F_{1\to 2} = \frac{1}{A_1}\int_{A_1}\int_{A_2}\frac{\cos\theta_1\cos\theta_2}{\pi s^2}\,\mathrm{d}A_2\,\mathrm{d}A_1$$

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

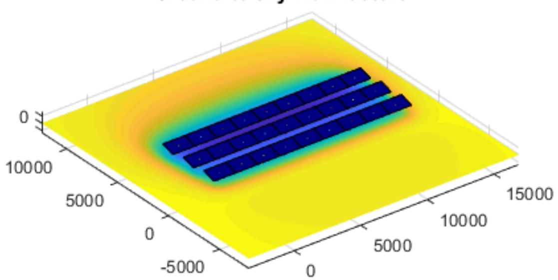
$$E_{ground,k}(t) = \sum_i \alpha_i G_i(t)VF_{i\to k}$$

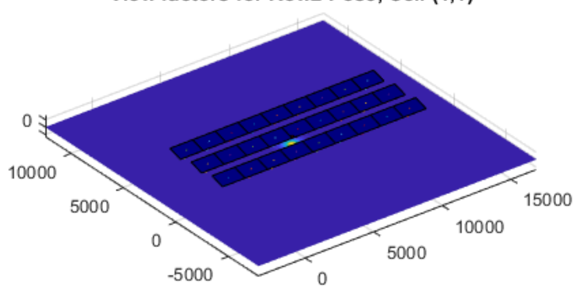


Backside irradiance map



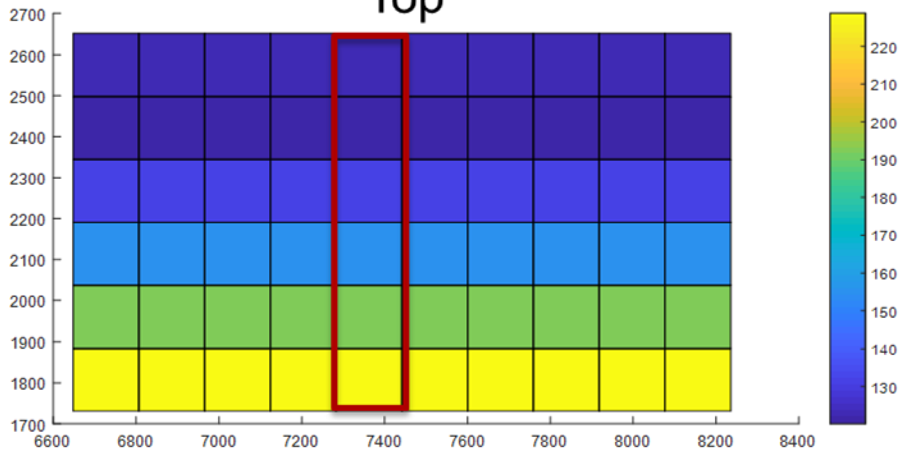
- Backside irradiance is calculated for each 2D cell
- Ground irradiance is calculated on a 2D grid
- Other modules and structures cast shadows on ground but do not directly reflect light to cells.



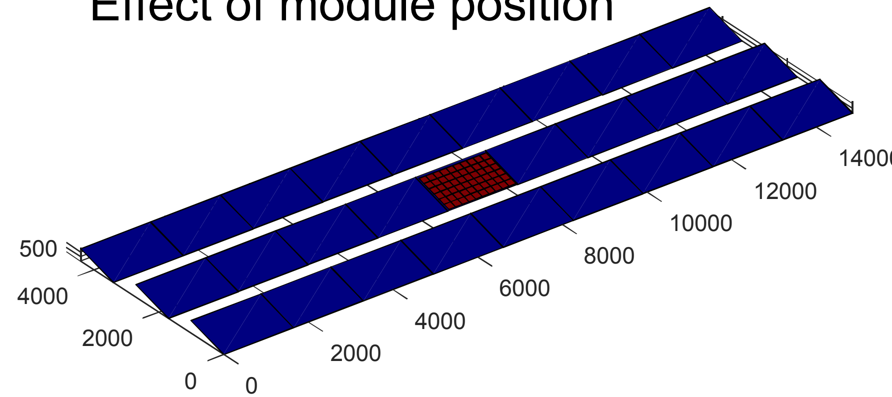


Example “3D”VF Results

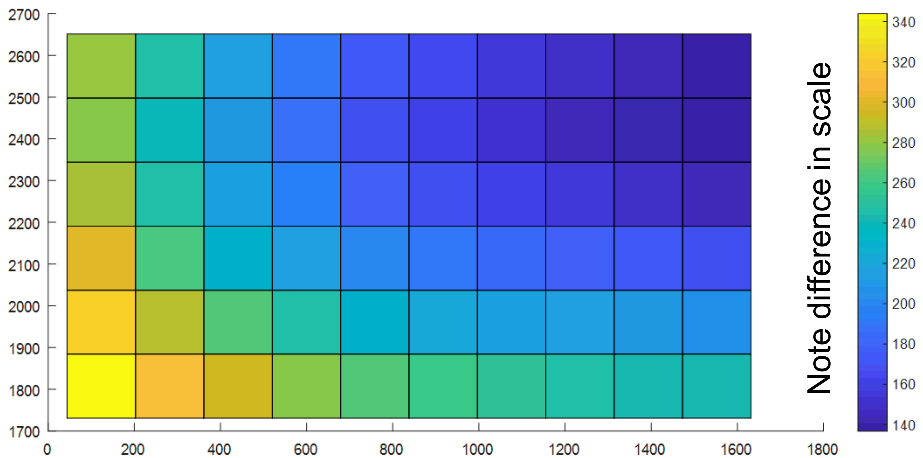
Top



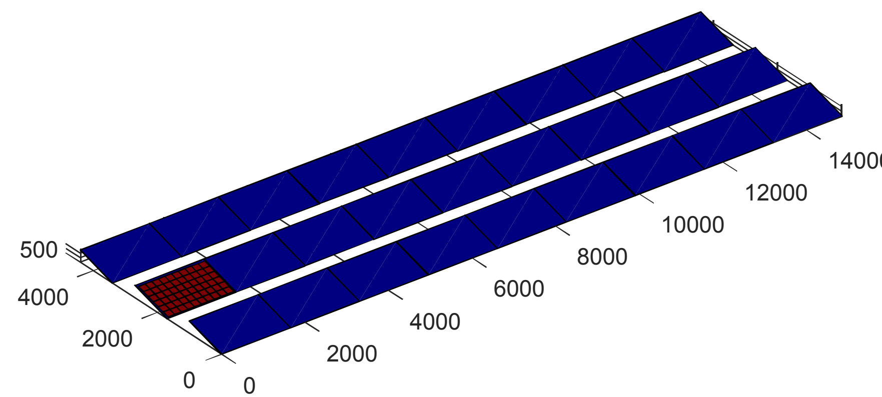
Effect of module position



Bottom



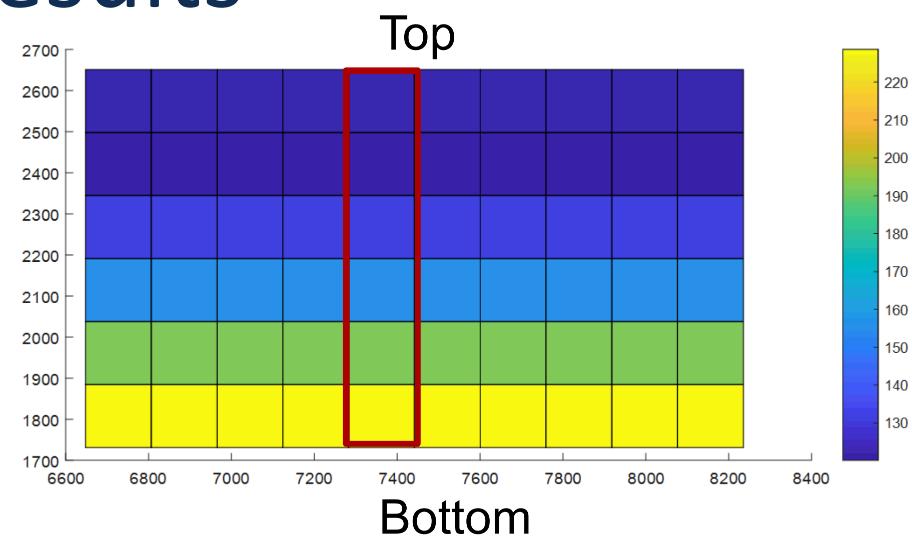
Note difference in scale

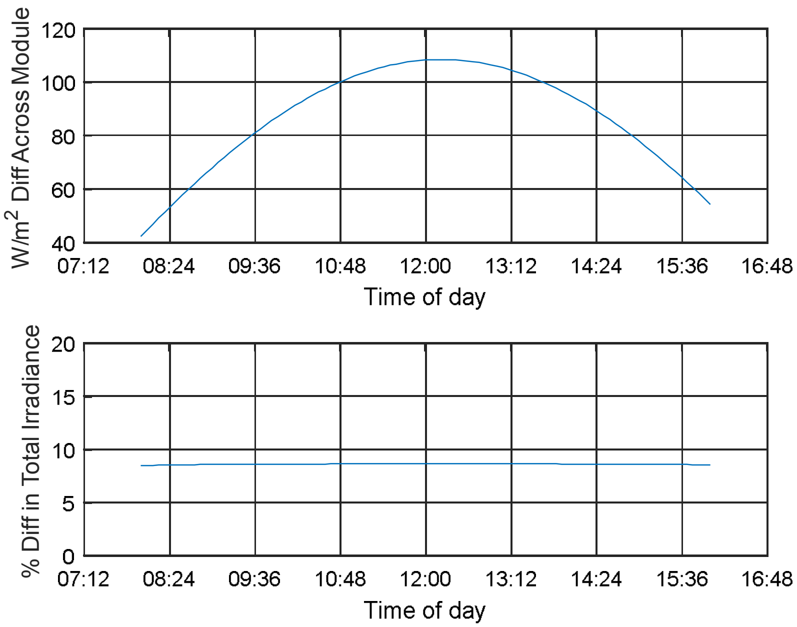


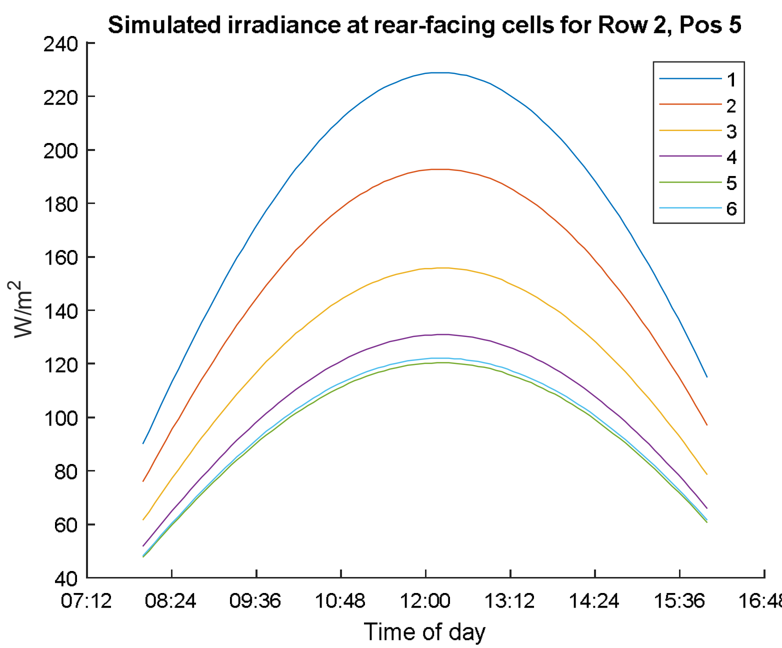
Solar noon on the spring equinox.

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

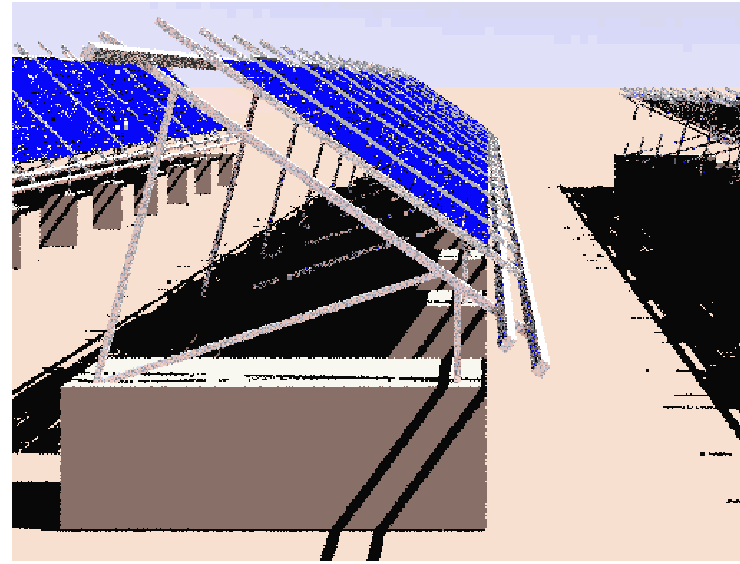


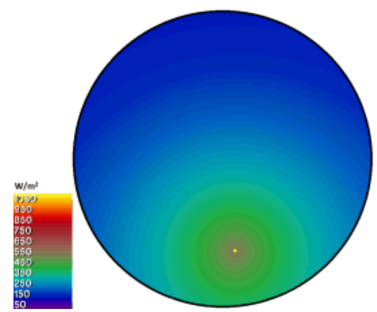




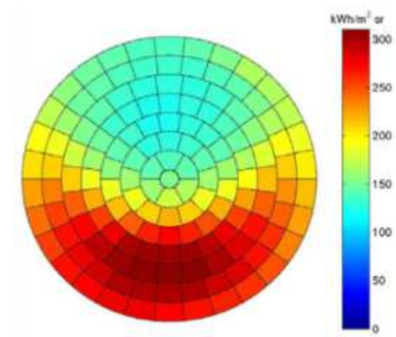
3D Ray Trace Model

- 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 approach[1] integrates time varying irradiance into annual insolation.





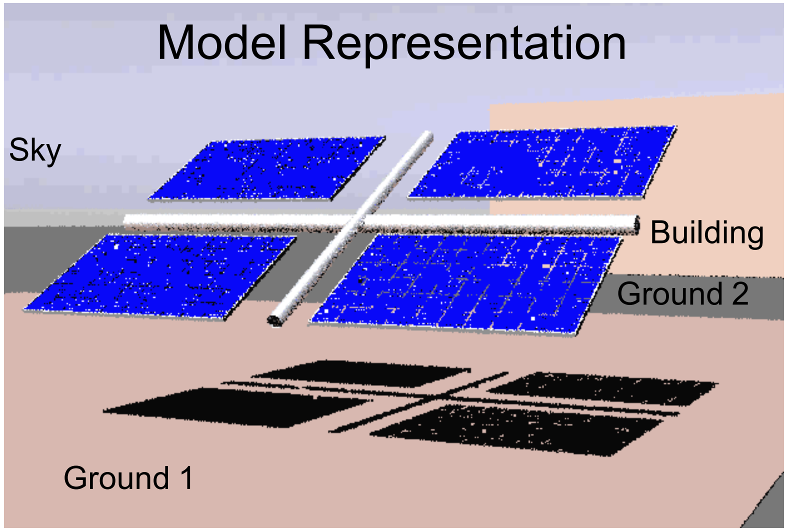
Single hourly Perez sky (W/r



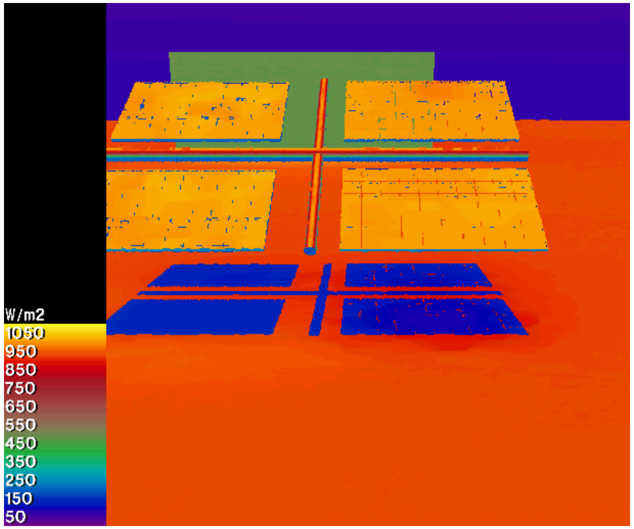
Annual cumulative sky conditions (kWh/m^2)

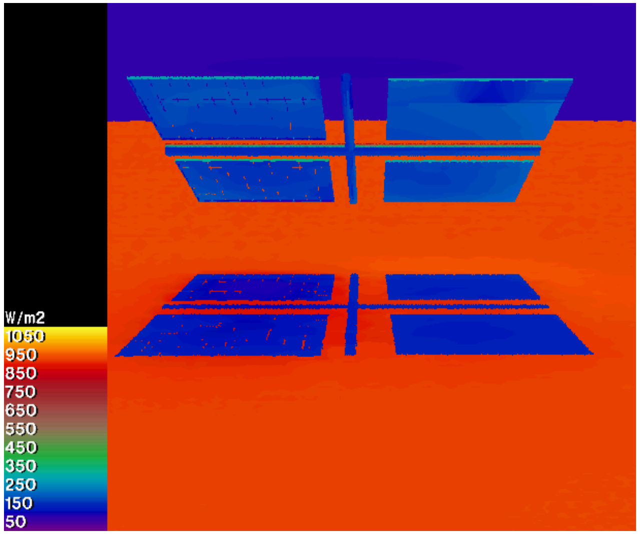
Example Ray Trace Results

Real system

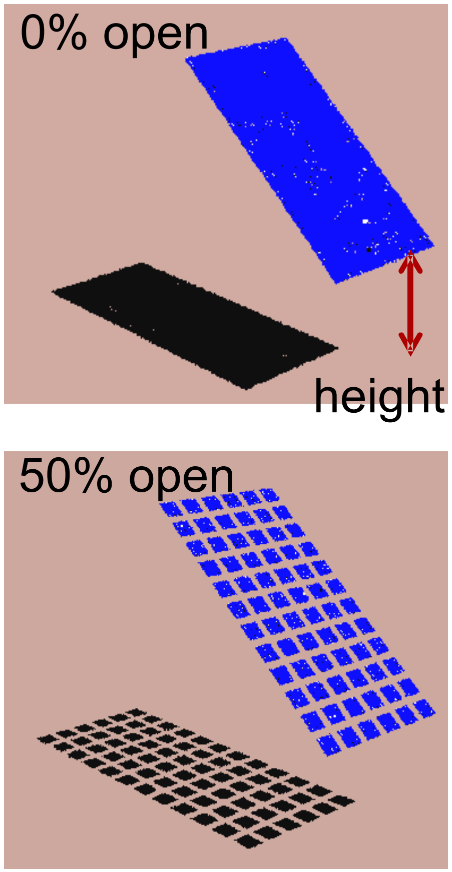


Irradiance Results

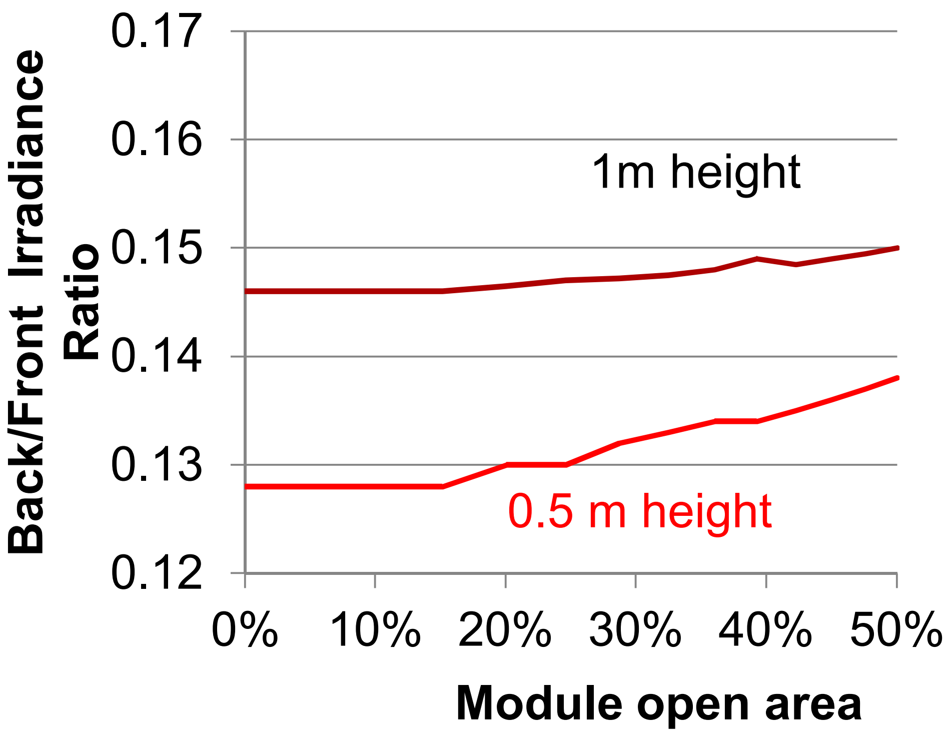




Example Ray Trace Results



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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