Exceptional service in the national interest

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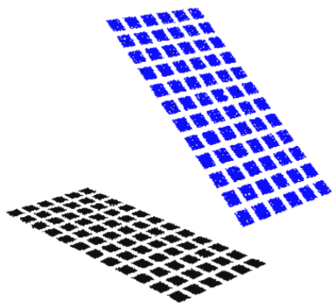
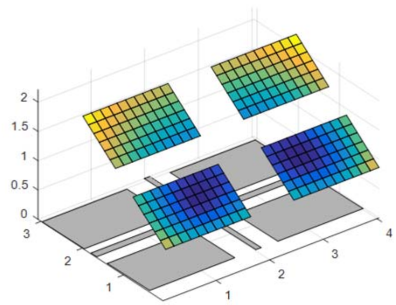
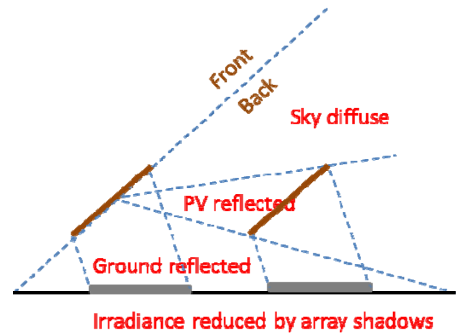






Irradiance Modeling for Bifacial PV

Clifford Hansen

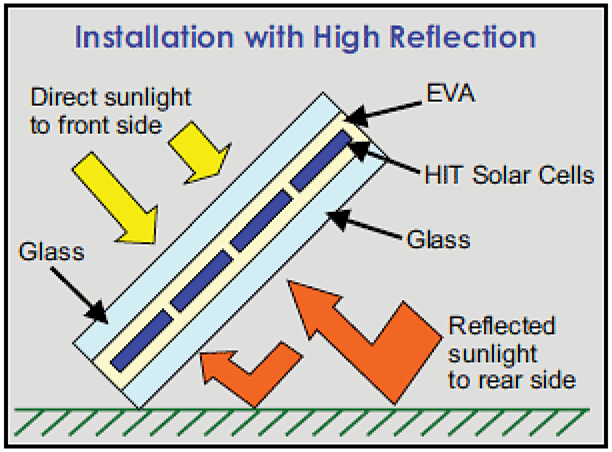
May 9, 2016

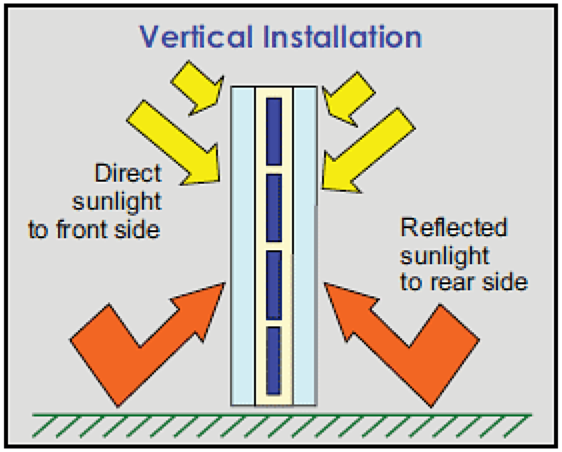
5th PV Performance Modeling Workshop

U.S. DEPARTMENT OF ENERGY NNSA

Bifacial PV modules

- Bifacial PV cells are processed to accept light from both sides of the cell.
- Bifacial modules incorporate bifacial cells and a transparent backsheet or glass-glass construction.
- Studies indicate bifacial PV can produce as much as 10 to >20% more energy with the same footprint as monofacial
- Targeted for white commercial roofs





Technical challenges of Bifacial PV

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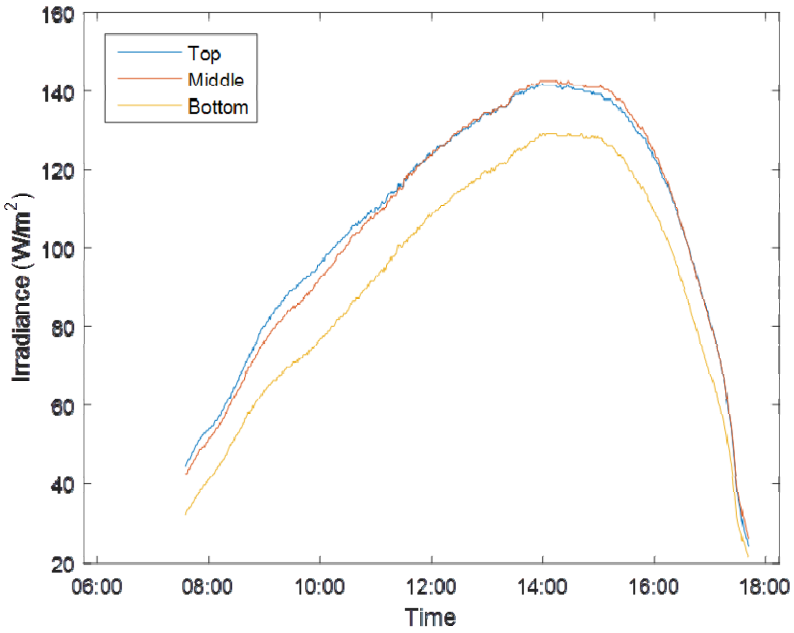
- Rating standards do not exist for bifacial PV modules
- Current PV performance models do not include models for bifacial arrays.
  - Back surface irradiance resource models are needed
  - Effects of non-uniform back surface irradiance on module performance
- Uncertainty on how bifacial gains scale with array size and design
  - Gains are high for small systems but are lower for larger systems.
  - Effects of cell spacing, row spacing, ground albedo, …
- Bifacial field data is not widely available.

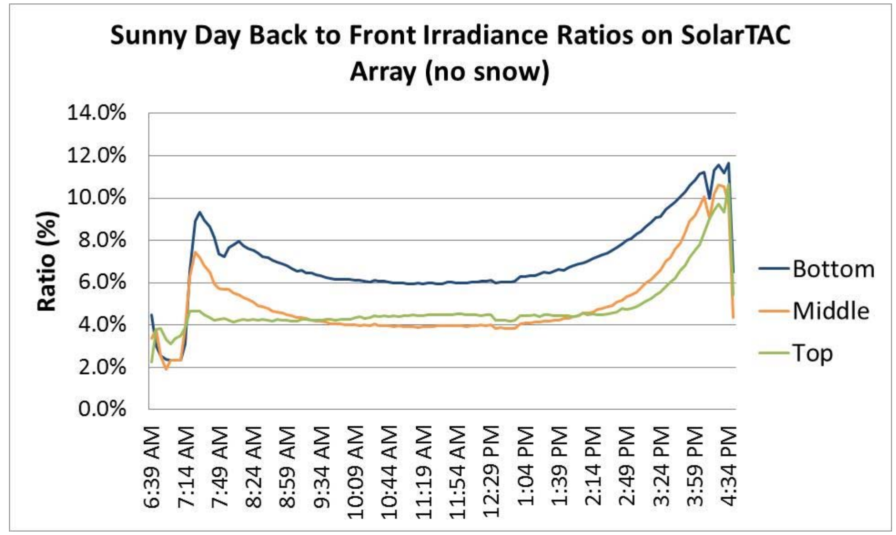
Example back surface irradiance data

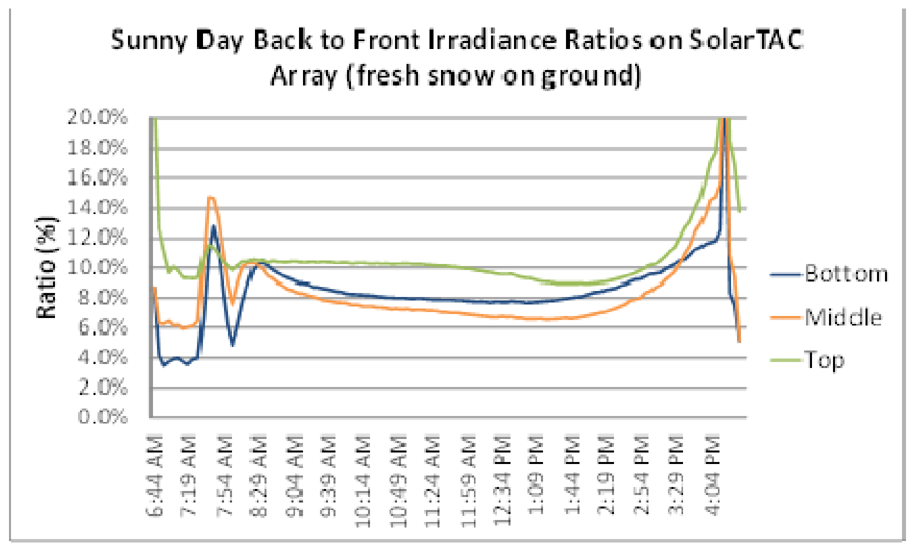
- Reference cells mounted behind a conventional array at NREL



East ⟷ West

SolarTAC Array (slide courtesy of NREL)





4-6% gain without snow;
7-10% with snow

SNL/NREL bifacial research project

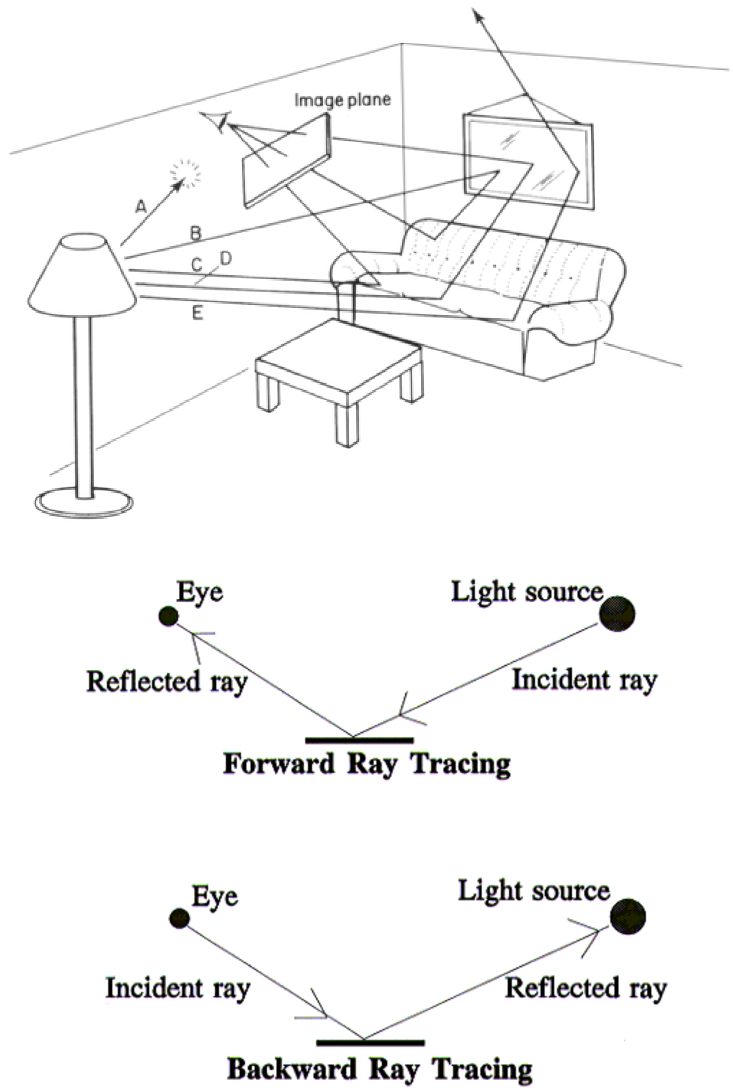
- Sandia, NREL, and University of Iowa are collaborating on a there year (FY16-18) research project to study bifacial PV
  - Monitored field installations (modules, string, and array scale)
  - Rating standards
  - Modeling approaches

IV tracing on modules

MPPT monitoring on modules

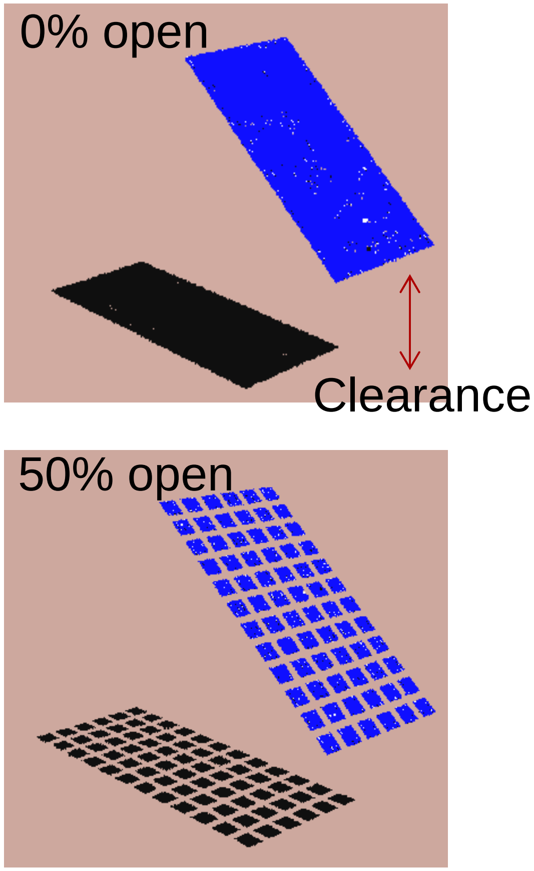
Ray tracing modeling tools

- COMSOL :
  - Commercial multiphysics software, ray optics module
  - Forward tracing
  - Can integrate with deformation models
- Radiance :
  - Open source NREL curated
  - Reverse ray tracing
  - Daylighting studies, integrated solar models
  - RGB, not broadband
  - ‘Clunky’ interface but can import from SketchUp

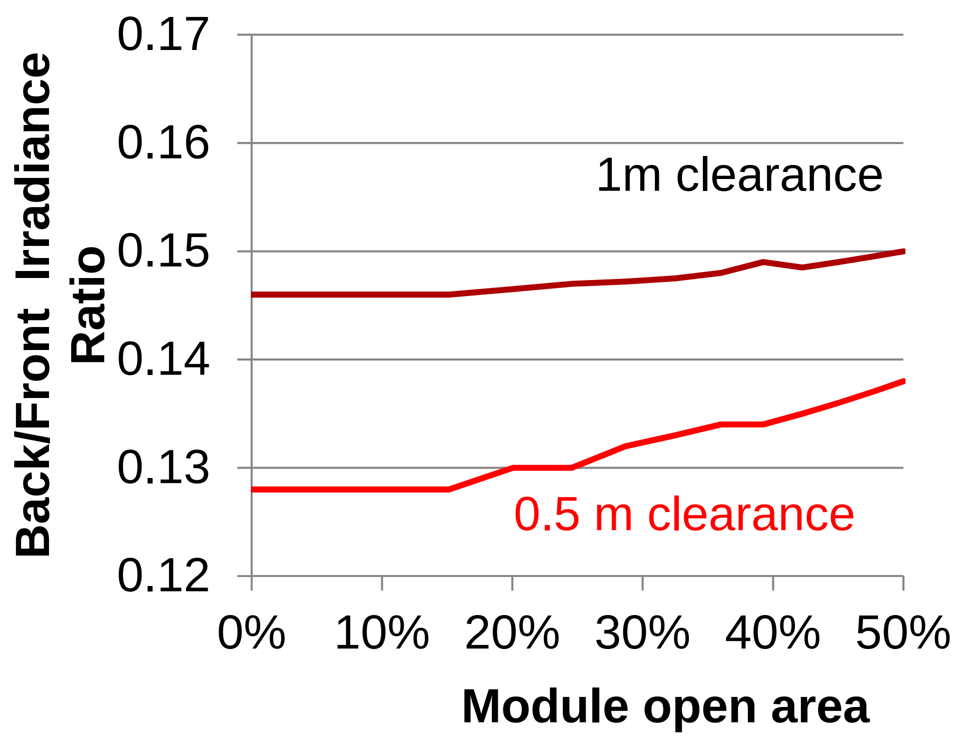


Credit: Dundalk Institute of Technology

Radiance example applications



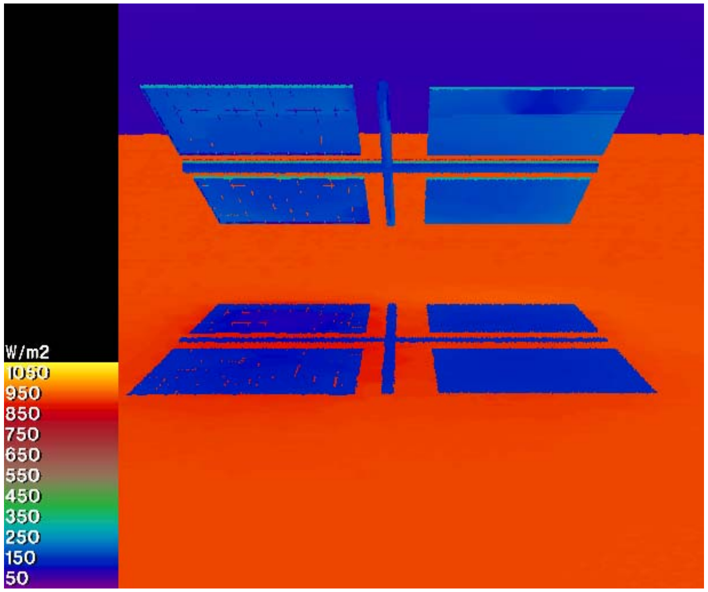
Investigate relationship between cell spacing and back-surface irradiance

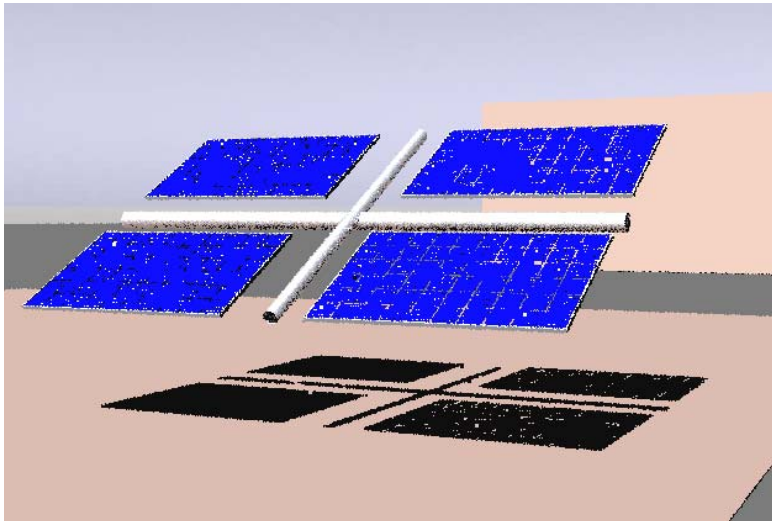


C. Deline et al., 2016 PVSC (forthcoming)

Ray tracing model advantages

- Can represent details of module construction and materials
- Can represent module mounting, nearby structures
- Non-homogenous ground reflectivity
- Detailed irradiance maps

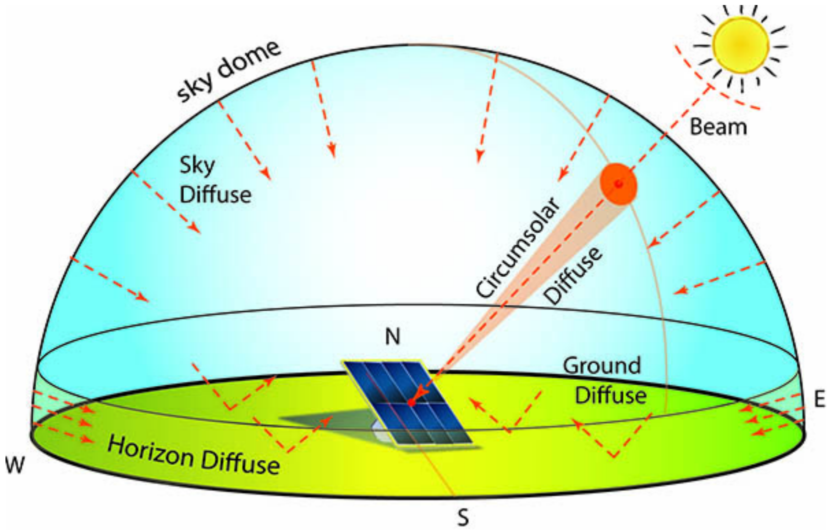




2 monofacial, 2 bifacial modules at 34° tilt

Ray tracing use considerations

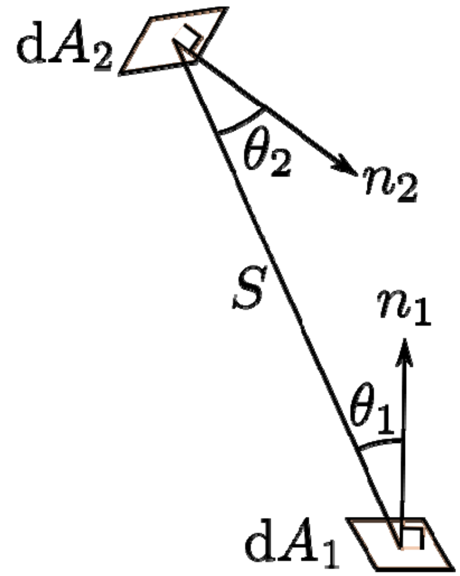
- Requires parameter values for material properties (reflectance, roughness, transmissivity, etc.)
- 3D geometric model (scene file)
- Computation time
  - Monte Carlo ray propagation
  - 40 sun positions ~ 4hrs for Radiance, COMSOL greater depending on mesh resolution
- COMSOL doesn't currently have solar functions (e.g., diffuse sky) in ray optics module



https://www.e-education.psu.edu/eme810/node/543

View factor models

- View factor (configuration, shape factor): fraction of radiation from A that strikes B
  - Knowledge base from radiation heat transfer
- Given view factor $F_{A1\to A2}$ and irradiance E1 leaving surface A1, the irradiance on A2 from A1 is $F_{A1\to A2} \times$ A1
- So total irradiance on A2 = Σ (F × A)
- However,
  - Assumes isotropic, diffuse reflections

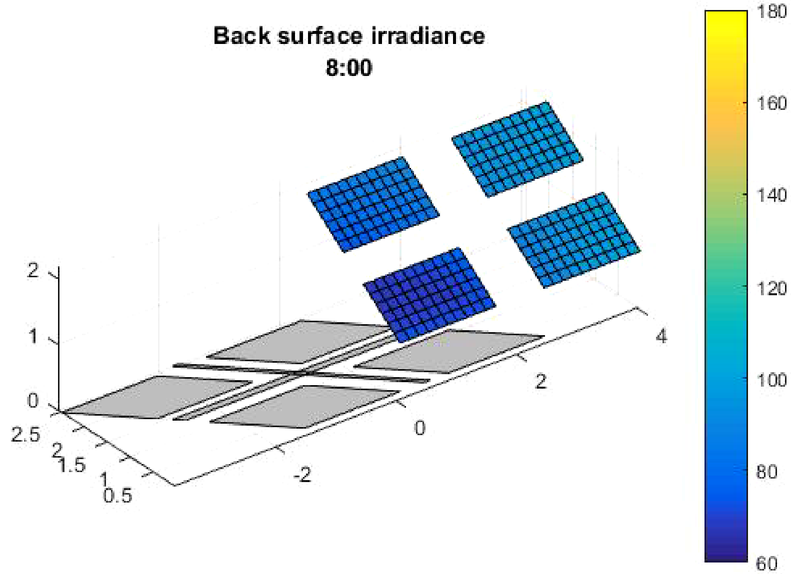


$$F_{1\to 2} = \frac{1}{A_1}\int_{A_1}\int_{A_2}\frac{\cos\theta_1\cos\theta_2}{\pi s^2}\,dA_2\,dA_1$$

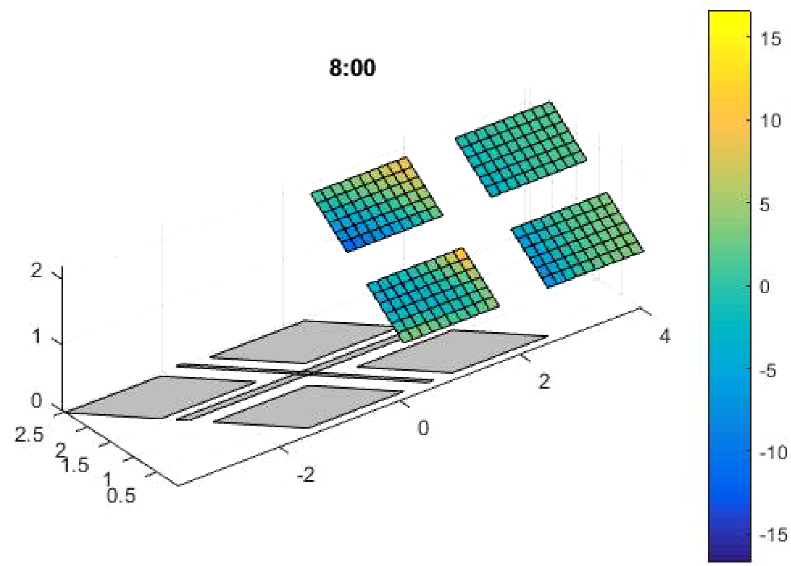
Cell level view factor model

- Integration isn't too bad with rectangular areas
- 'Cell level' VF model (Sandia) computes VF_S from shadowed area behind an array to each cell on the back surface
  - VF_{NS} from non-shaded area from VF algebra
- E(back) = VF_{NS} x GHI x $albedo_{NS}$ + VF_S x DHI x $albedo_S$
  - Assumes isotropic sky diffuse and ground reflections

Cell level view factor model



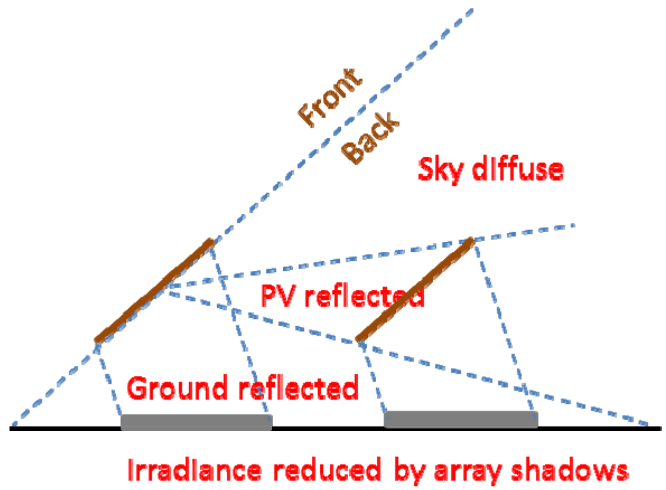
Back surface irradiance (W/m^2), clear sky conditions

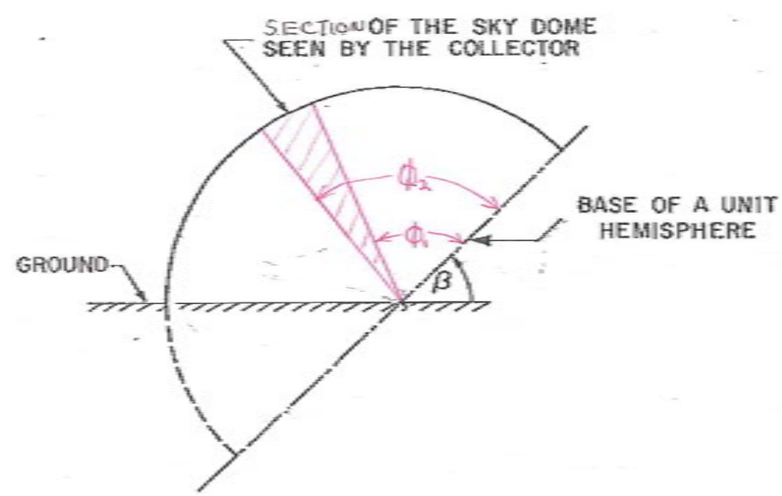


Deviation (%) from module average back surface irradiance, clear sky conditions

Array-scale view factor model

- NREL (Bill Marion)
- 2D geometry
  - Neglects 'end' effects
  - Allows for simple closed expressions for view factors
- Easily accommodates
  - Detailed sky diffuse model (horizon, circumsolar and rest-of-sky)
  - Reflection from row behind
  - Sky obscuration by row in front





$$VF_{section} = \frac{1}{2}(\cos \Phi_1 - \cos \Phi_2)$$

Summary

- Ray tracing:
  - Module/rack/mounting design trade-offs and optimization
  - Requires greatest effort and time to configure and run
  - May be overkill for performance modeling
- Cell level VF model:
  - Computation effort is reasonable (~1 minute for 40 sun positions in Matlab) but not going to be a spreadsheet
  - Scene description – coordinate systems, positions, dimensions
  - Seems best suited for small arrays or non-traditional configuration (e.g., N-S vertical modules)
- Array scale VF model:
  - Relatively easy to configure, fast computation
  - Likely the practical choice for energy prediction for conventional arrays