Performance model for bifacial PV modules

8th PVPMC Performance Modeling and Monitoring Workshop
Albuquerque, New Mexico
May 9-10, 2017

Clifford Hansen and Daniel Riley
Sandia National Laboratories,
Albuquerque, NM USA

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525..

PVPerformance MODELING COLLABORATIVE

Exceptional service in the national interest

Sandia National Laboratories

SAND2017-5155 C

PV Performance Modeling Process

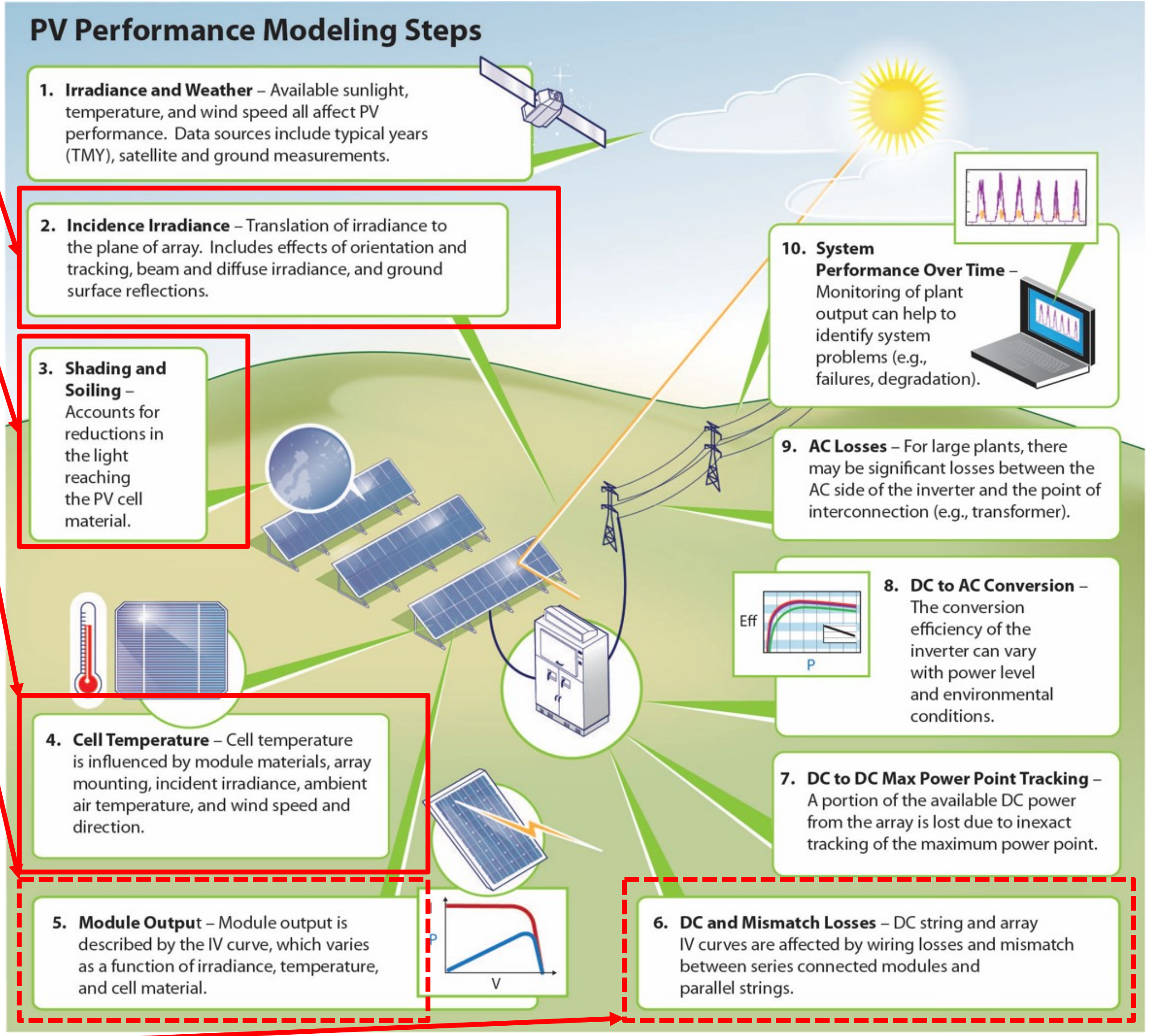
Irradiance on rear surface

Shading on rear surface

Cell temperature prediction

Cell mismatch effect on module current and voltage

Module mismatch effect on string current and voltage



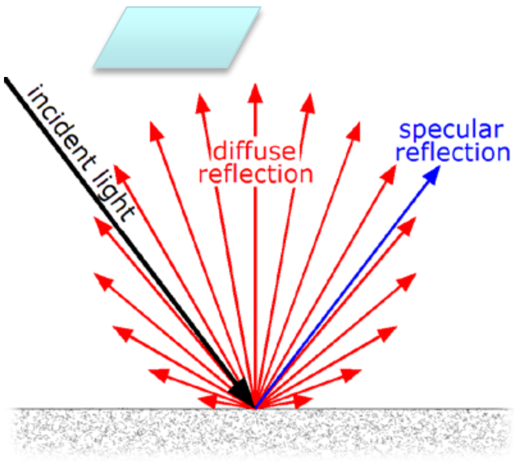
Rear surface irradiance model

- View factor (configuration, shape factor) $F_{A1 \rightarrow A2}$ = fraction of radiation from A1 that strikes A2
  - Assumes diffuse reflection of irradiance on A1
- Irradiance (W) on surface A2 from A1

  $G_{A1,A2} = \alpha \times G_{A1} \times F_{A1 \rightarrow A2}$
- Total irradiance on A2:

$$G_{A2} = \alpha \times \sum_{i} G_{A_i,A2} \times F_{A_i \rightarrow A2}$$

- Irradiance on a rear-surface cell from:
  - Reflections from shaded ground
  - Reflections from unshaded ground
  - Sky diffuse
  - Direct beam
  - *Specular reflections*



Module-Scale Adjustable Rack

Holds four modules
- -2 bifacial
- -2 monofacial

Reference Cells
- -2 front facing
- -3 back facing

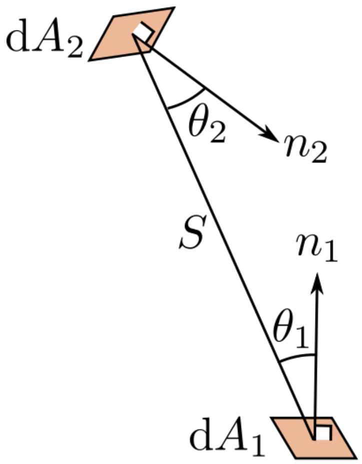
Multitracer
- -measures IV curves and module temps

Variables
- -Height
- -Tilt
- -Albedo

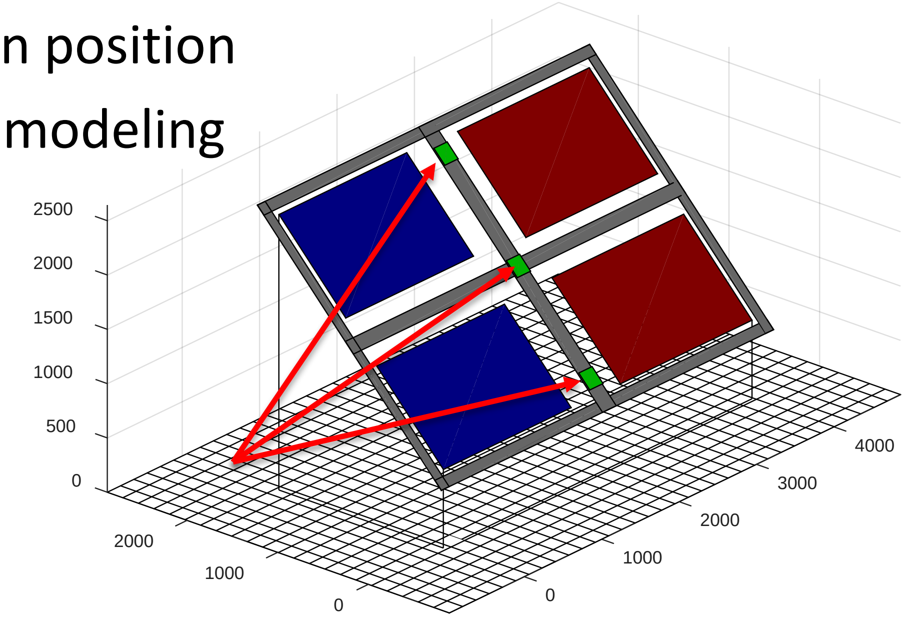
Efficiently calculating view factors

- Formal approach

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



- Massively parallel algebraic computation for PV
  - Grid the ground (emitting) surface
  - For each grid cell, compute VF to each receiving cell
- VFs depend on geometry NOT sun position
- Compute once before irradiance modeling



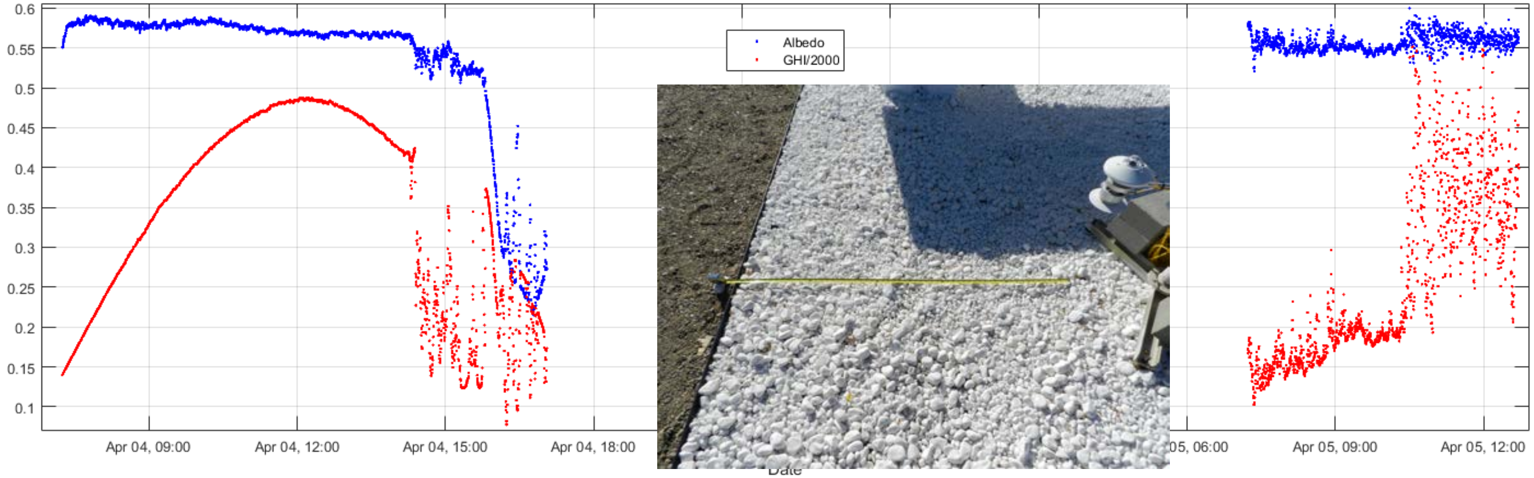
- Approximate integrals with value at centroids of each cell
- cos computed by matrix product
- Fast enough on CPU, anticipate x100 speedup expected on GPU

Rear surface irradiance model

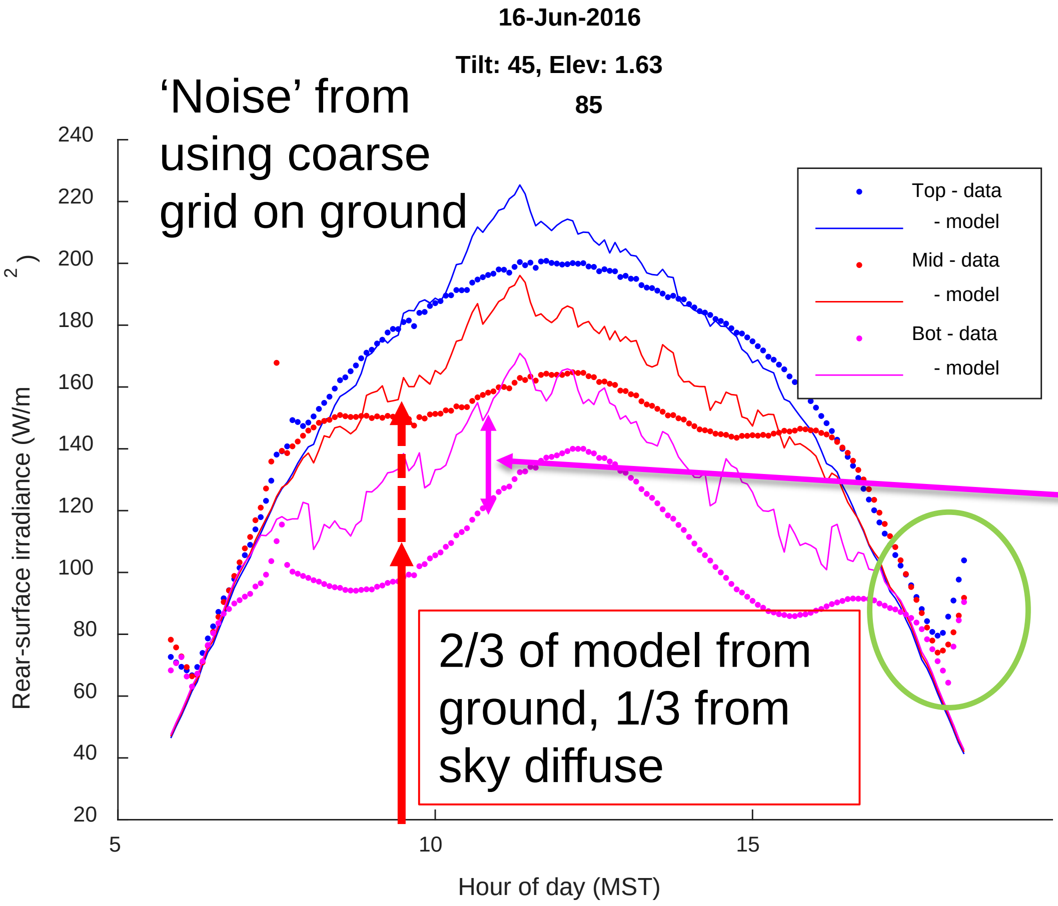
- G (W/m2) on rear surface = ground reflected + sky diffuse *(+ direct + specular)*

$$G_{A2} = \sum_i G_{A_i,A2} \times F_{A_i \to A2}$$

- Ground reflected from a grid cell:
  - Shaded cell: G = DHI $\times$ $VF_{\text{cell to sky}}$ = DHI currently
    - Grid cell on the ground doesn't 'see' entire sky dome
    - Part of sky is occluded by array objects (e.g., modules)
  - Unshaded cell: G = DNI $\times$ cos(zenith) + DHI ($\times$ $VF_{\text{cell to sky}}$)
- Albedo (example over white rocks with nearby shadowing)



Rear surface irradiance model - results

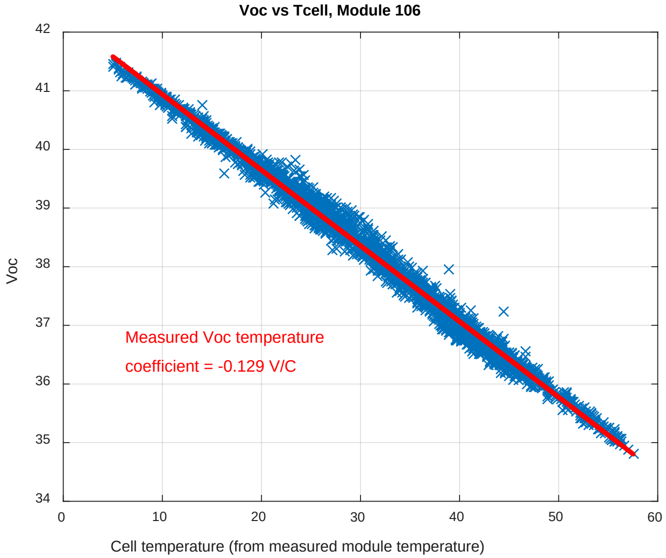


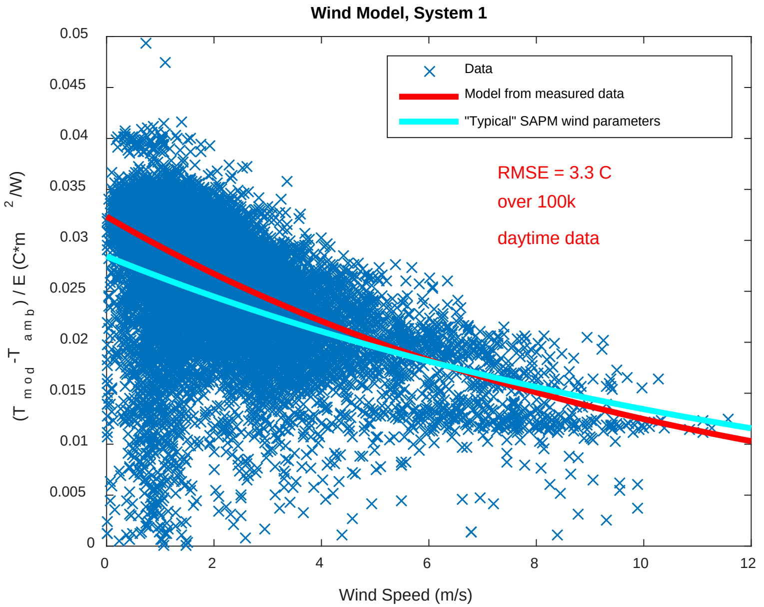
Overestimate - 'extra' diffuse from $VF_{cell\ to\ sky} = 1$??

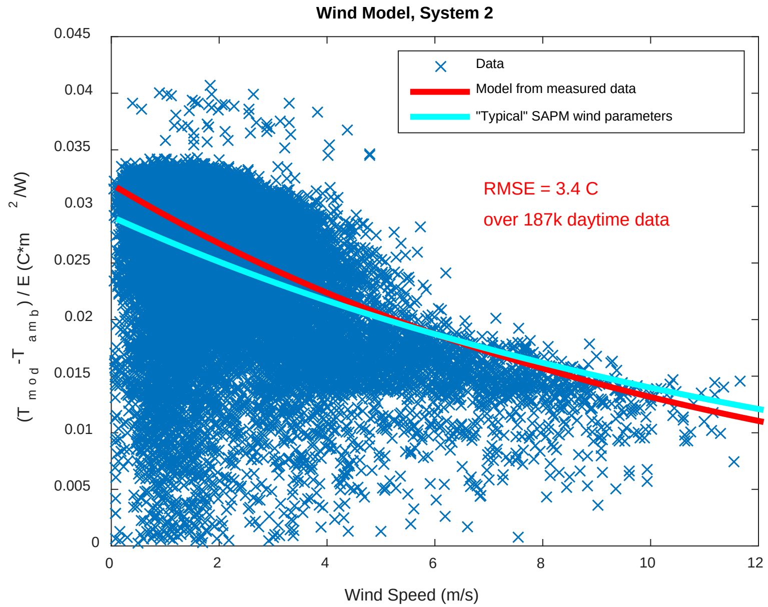
Direct light from sunrise and sunset behind array

Cell temperature model

- For bifacial modules
  - Do V_{OC} and T_{cell} relationships still apply?
  - Can we still estimate T_{module} from environmental data such as E, $T_{ambient}$, wind speed?



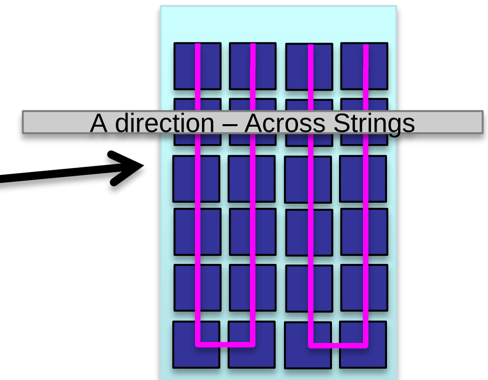


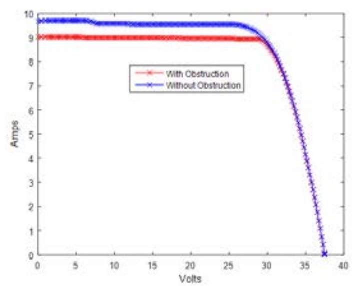


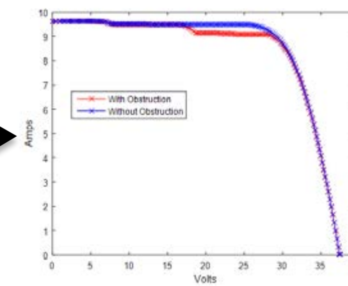
Effects of rear-surface shading

Sandia National Laboratories

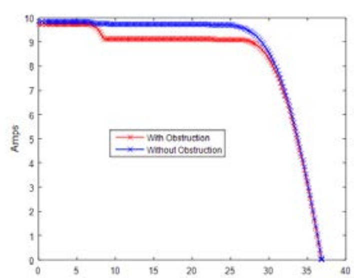
- What effect do obstructions near the rear surface have on the IV curve?
  - Size of obstruction relative to module active area?
  - Obstruction distance from back surface?
    - My tests, distance is 0 (hard shade) and 5.9 cm (soft shade)
  - Orientation of obstruction relative to module stringing?
  - Obstruction covers one cell string or multiple cell strings?
  - Multiple obstructions?

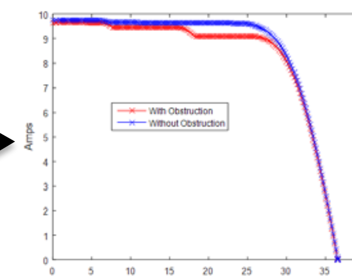






10% of active rear surface covered

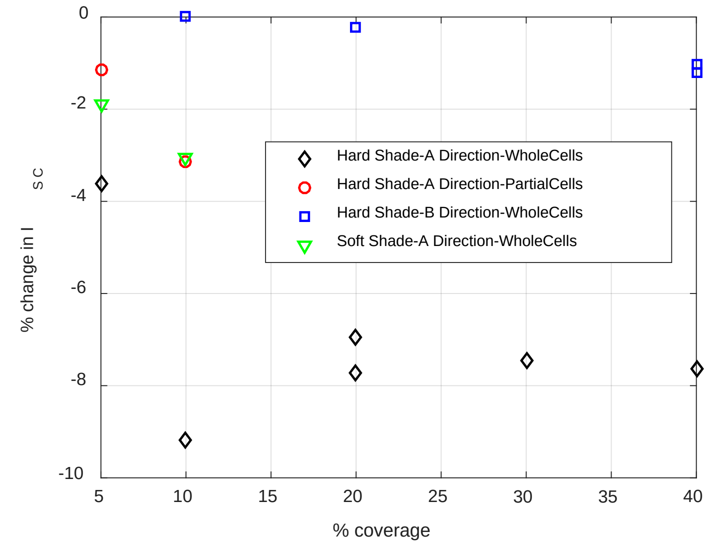


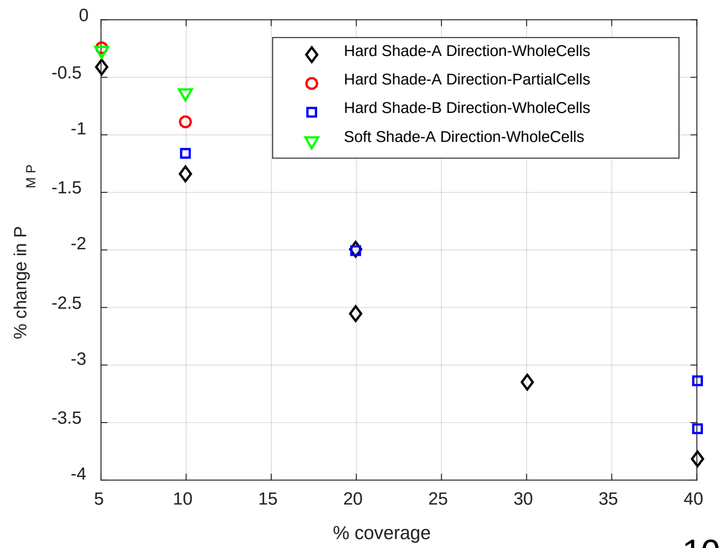


40% of active rear surface covered

Effects of rear-surface shading

- Reductions are primarily in current, not voltage
- Shade orientation has a large effect on I_{SC} but little effect on I_{MP} and P_{MP}
- Coverage ratio is the most important factors for determining P_{MP}, followed by the amount of space between the module and the obstruction (soft vs. hard shade)
- Orientation of the obstruction has little effect on P_{MP}, perhaps 0.5% or less in typical installations



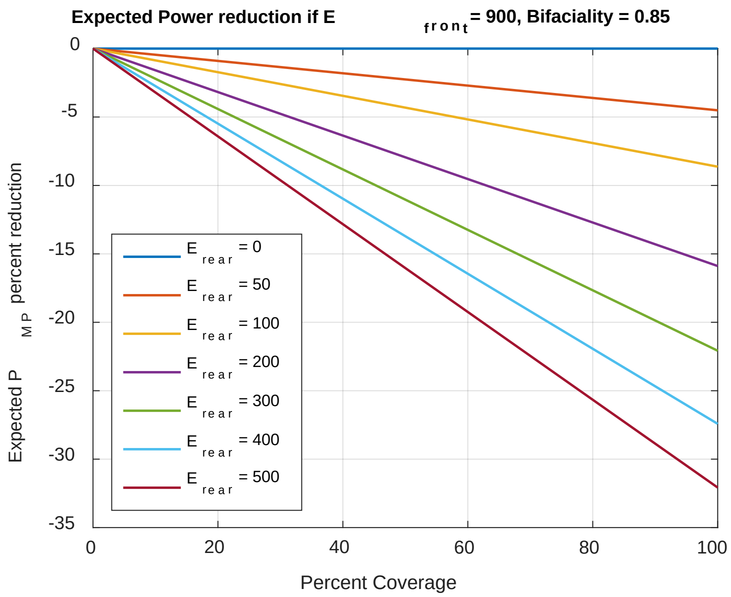


Effects of rear-surface shading

- Since coverage ratio is the most important factor for determining P_{MP} reductions, we can approximate the losses caused by rear-surface shading with a simple model requiring only the coverage ratio, module bifaciality, and relevant irradiances. For hard-shade:

$$PmpReductionFraction = \frac{E_{front} + E_{rear} \times BiFi_{Pmp} \times (1 - CoverageRatio)}{E_{front} + E_{rear} \times BiFi_{Pmp}} - 1$$

- Additional testing with obstruction distances may yield a modification to the model to reduce losses as a function of obstruction distance from the module.



What’s next

- Completion and validation of rear-surface irradiance model component
  - Ground-to-sky view factors
- Electrical performance model
  - Module Pmp ~ POA (front) + SF × average(rear surface irradiance)
  - Predicting IV curve looks more challenging
    - E.g., effect of rear-surface shading on Isc
- Mismatch modeling
  - Cell-to-cell irradiance on rear surface, module-to-model mismatch in current
  - Hope for a derate factor
- Validation of performance model