

Performance model for bifacial PV modules

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PVPerformance
MODELING COLLABORATIVE

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PV Performance Modeling Process

PV Performance Modeling Steps

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

1. Irradiance and Weather – Available sunlight, temperature, and wind speed all affect PV performance. Data sources include typical years (TMY), satellite and ground measurements.

2. Incidence Irradiance – Translation of irradiance to the plane of array. Includes effects of orientation and tracking, beam and diffuse irradiance, and ground surface reflections.

3. Shading and Soiling – Accounts for reductions in the light reaching the PV cell material.

4. Cell Temperature – Cell temperature is influenced by module materials, array mounting, incident irradiance, ambient air temperature, and wind speed and direction.

5. Module Output – Module output is described by the IV curve, which varies as a function of irradiance, temperature, and cell material.

10. System Performance Over Time – Monitoring of plant output can help to identify system problems (e.g., failures, degradation).

9. AC Losses – For large plants, there may be significant losses between the AC side of the inverter and the point of interconnection (e.g., transformer).

8. DC to AC Conversion – The conversion efficiency of the inverter can vary with power level and environmental conditions.

7. DC to DC Max Power Point Tracking – A portion of the available DC power from the array is lost due to inexact tracking of the maximum power point.

6. DC and Mismatch Losses – DC string and array IV curves are affected by wiring losses and mismatch between series connected modules and parallel strings.

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

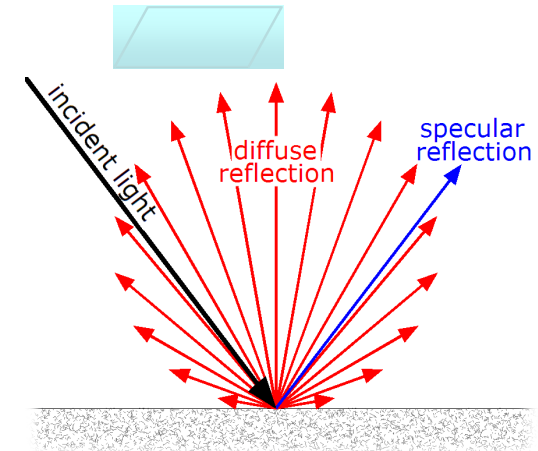
$$G_{A1,A2} = \alpha \times G_{A1} \times F_{A1 \rightarrow A2}$$

- 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*



By GianniG46 - Own work, CC BY-SA 3.0,
<https://commons.wikimedia.org/w/index.php?curid=11902338>



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

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

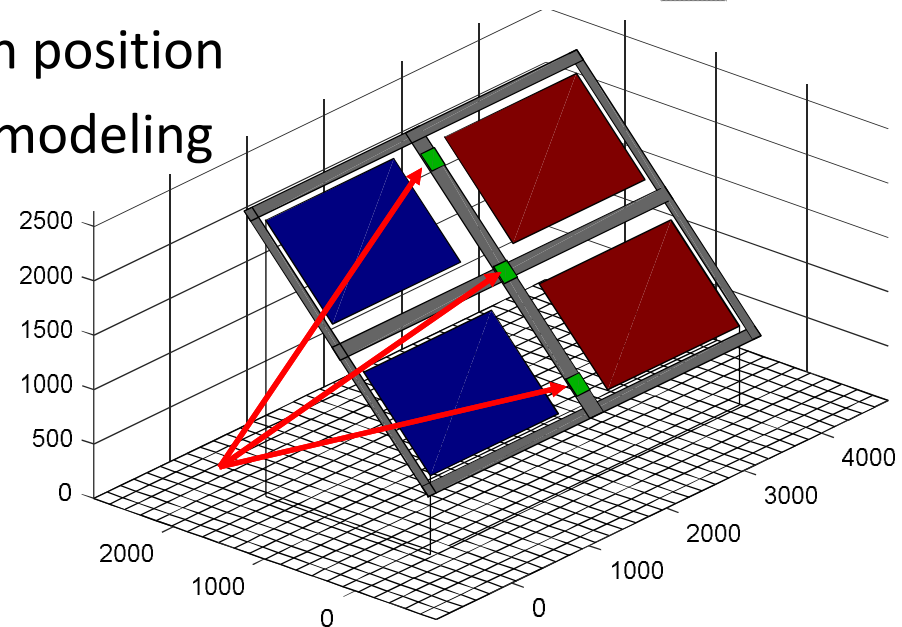
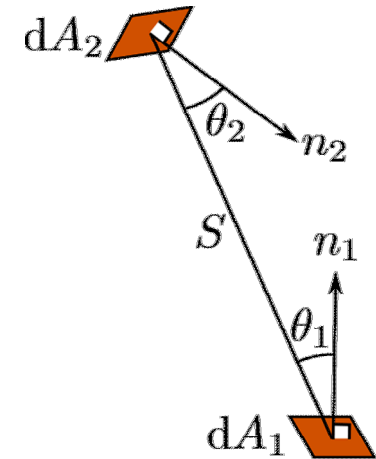
- Massively parallel algebraic computation for PV

- 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

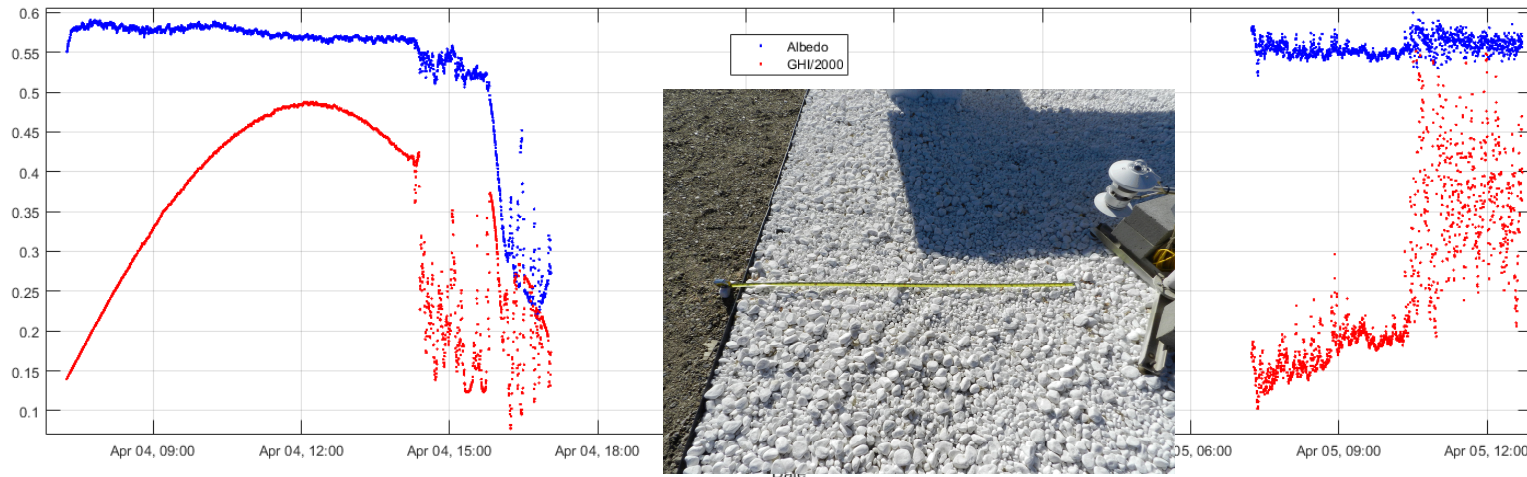
- Approximate integrals with value at centroids of each cell
- $\cos$ computed by matrix product
- Fast enough on CPU, anticipate x100 speedup expected on GPU



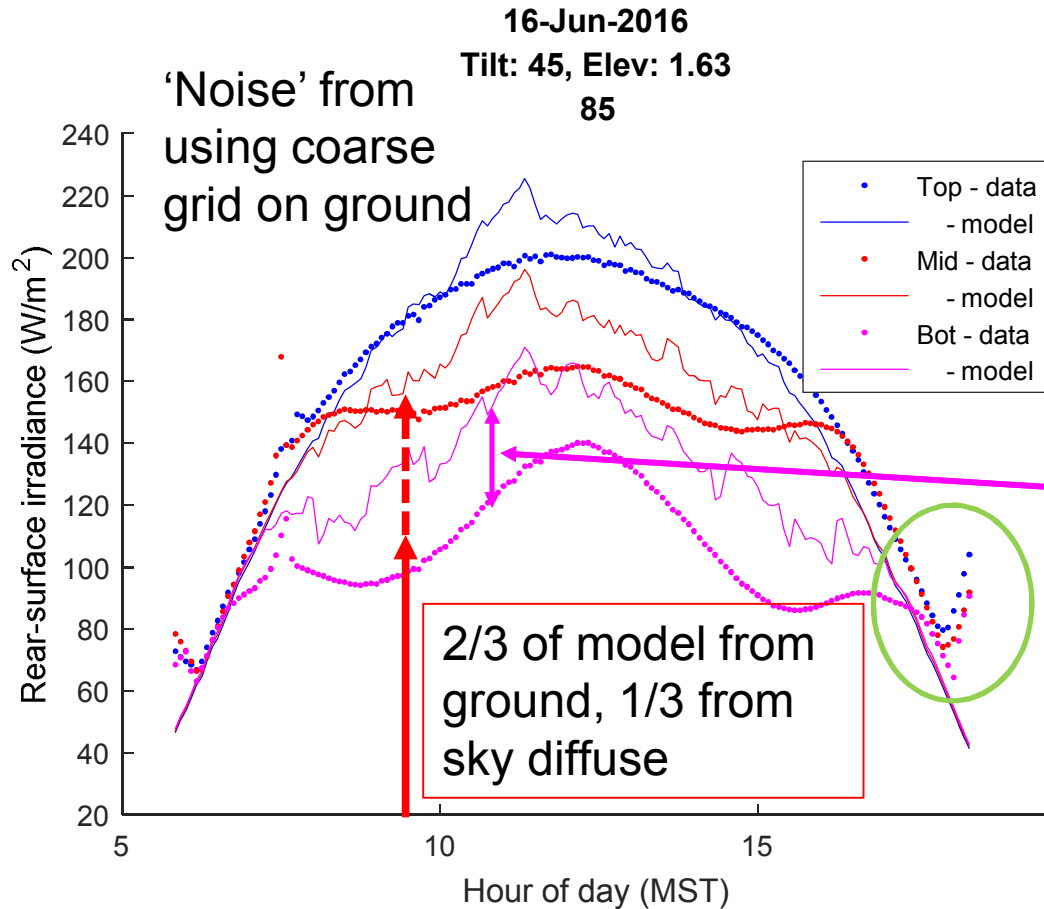
Rear surface irradiance model

- G (W/m²) on rear surface = ground reflected + sky diffuse (+ direct + specular)
- 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: $G = DNI \times \cos(\text{zenith}) + DHI (\times VF_{\text{cell to sky}})$
- Albedo (example over white rocks with nearby shadowing)

$$G_{A2} = \sum_i G_{A_i A2} \times F_{A_i \rightarrow A2}$$



Rear surface irradiance model - results

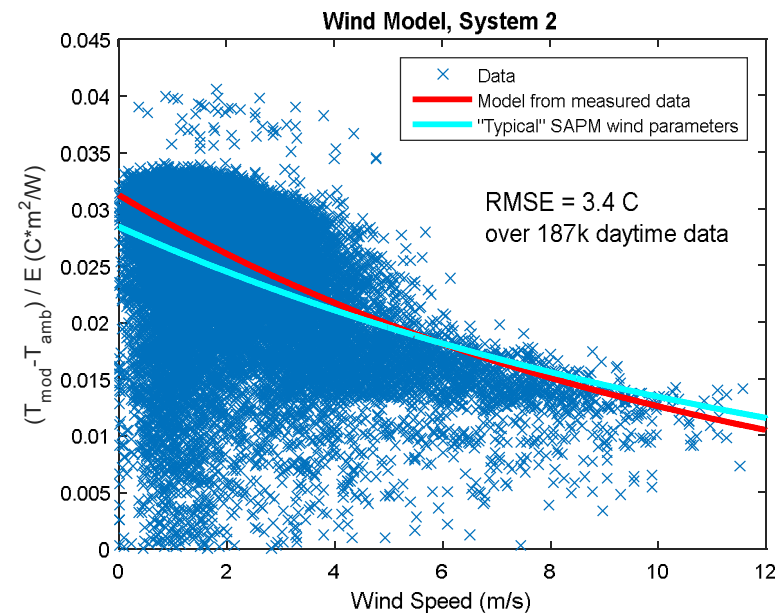
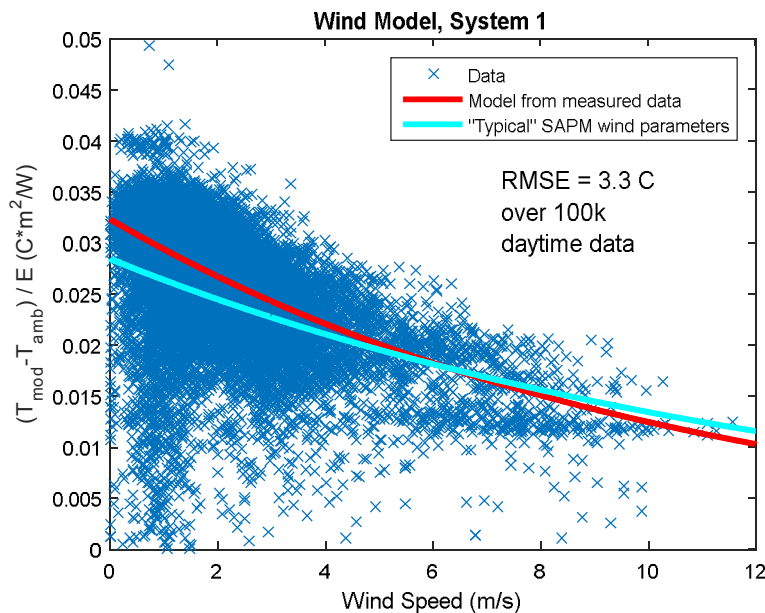
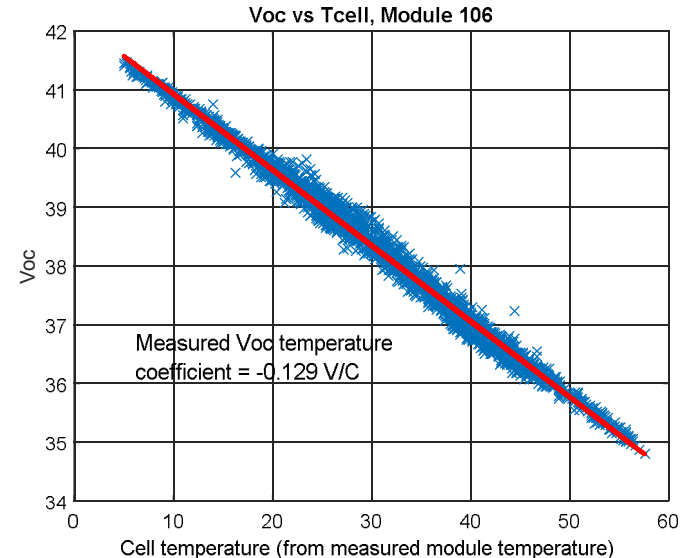


Overestimate - 'extra' diffuse from $VF_{\text{cell to sky}} = 1$??

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?

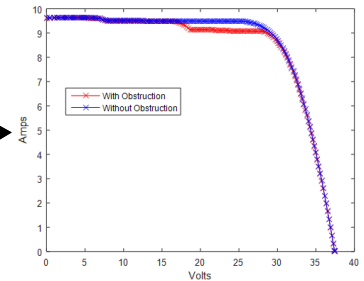
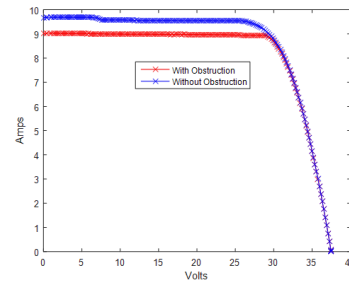
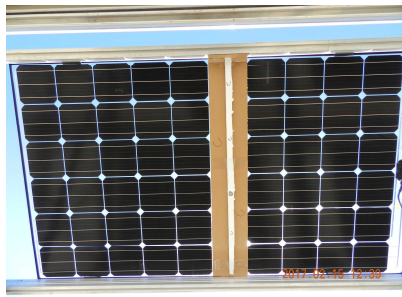
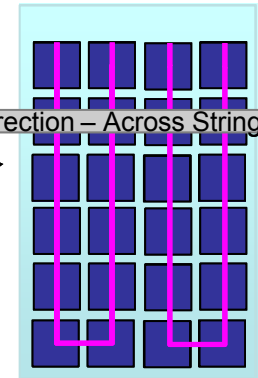


Effects of rear-surface shading

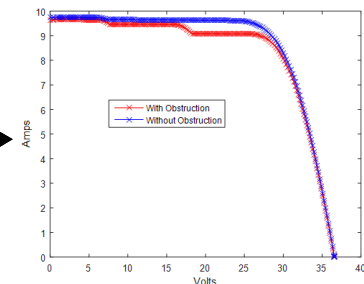
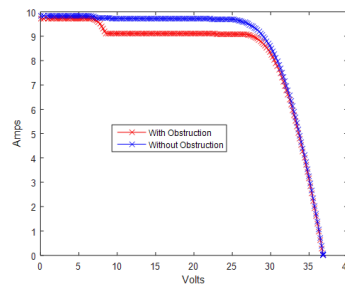
■ What effect do obstructions near the rear surface have on the IV curve?

- 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?

A direction – Across Strings



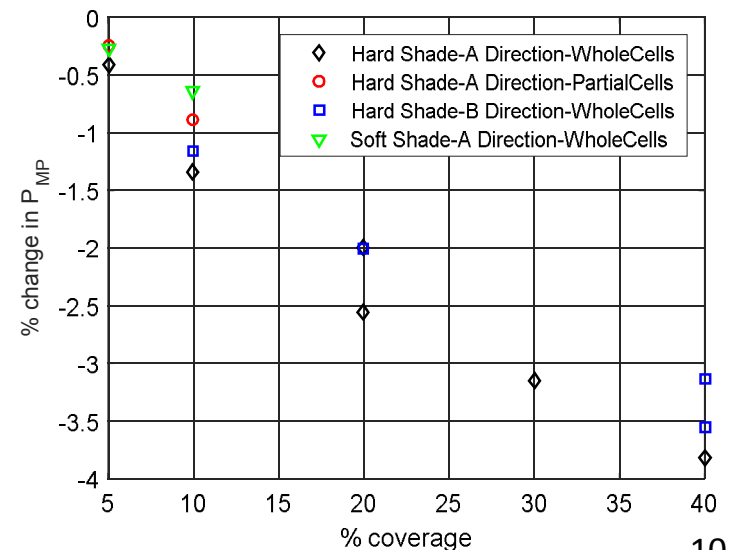
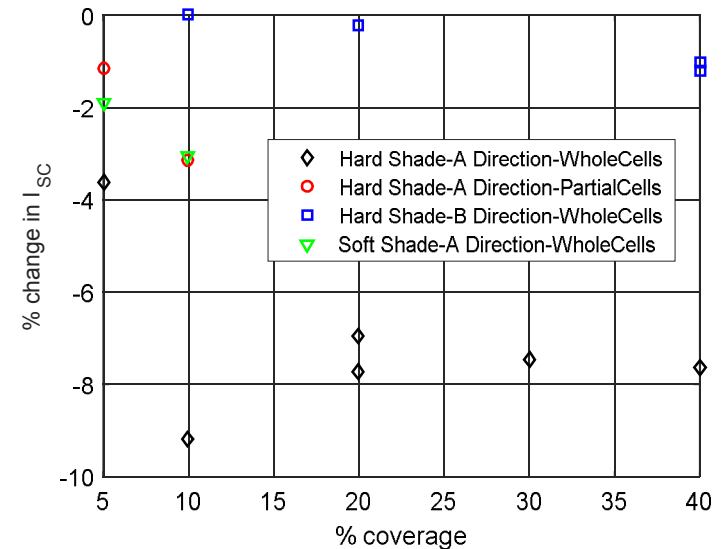
10% of active rear surface covered



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

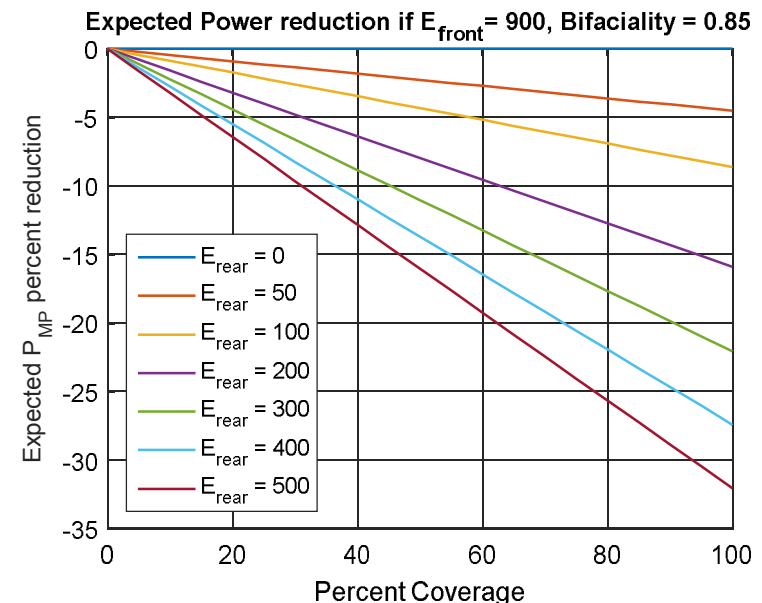


Effects of rear-surface shading

- 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:

$$P_{mp}ReductionFraction = \frac{E_{front} + E_{rear} \times BiFi_{P_{mp}} \times (1 - CoverageRatio)}{E_{front} + E_{rear} \times BiFi_{P_{mp}}} - 1$$

- 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
 - $\text{Module Pmp} \sim \text{POA (front)} + \text{SF} \times \text{average(rear surface irradiance)}$
 - Predicting IV curve looks more challenging
 - E.g., effect of rear-surface shading on I_{sc}
- Mismatch modeling
 - Cell-to-cell irradiance on rear surface, module-to-model mismatch in current
 - Hope for a derate factor
- Validation of performance model

