

# Performance model for bifacial PV modules

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Modeling and Monitoring  
Workshop  
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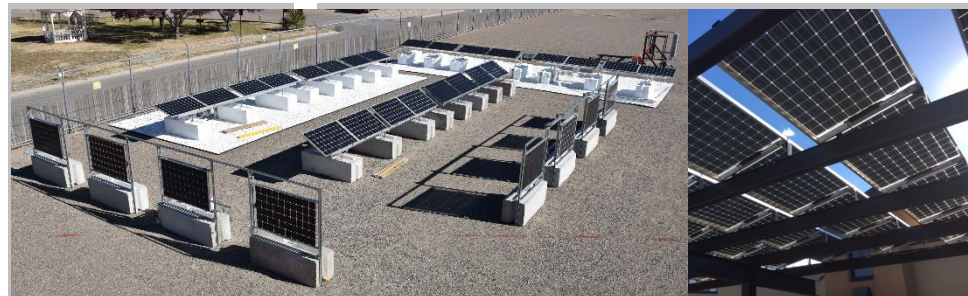


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# PV Performance Modeling Process

## 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

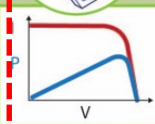
**1. Irradiance and Weather** – Available sunlight, temperature, and wind speed all affect PV performance. Data sources include typical years (TMY), satellite and ground measurements.

**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.

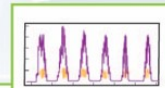
**3. Shading and Soiling** – Accounts for reductions in the light reaching the PV cell material.

**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.

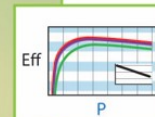


**10. System Performance Over Time** – Monitoring of plant output can help to identify system problems (e.g., failures, degradation).



**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

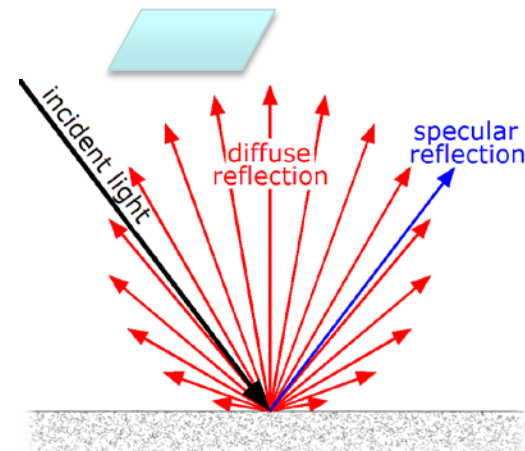
$$G_{A1,A2} = \alpha \times G_{A1} \times F_{A1 \rightarrow A2}$$

- 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*



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# 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

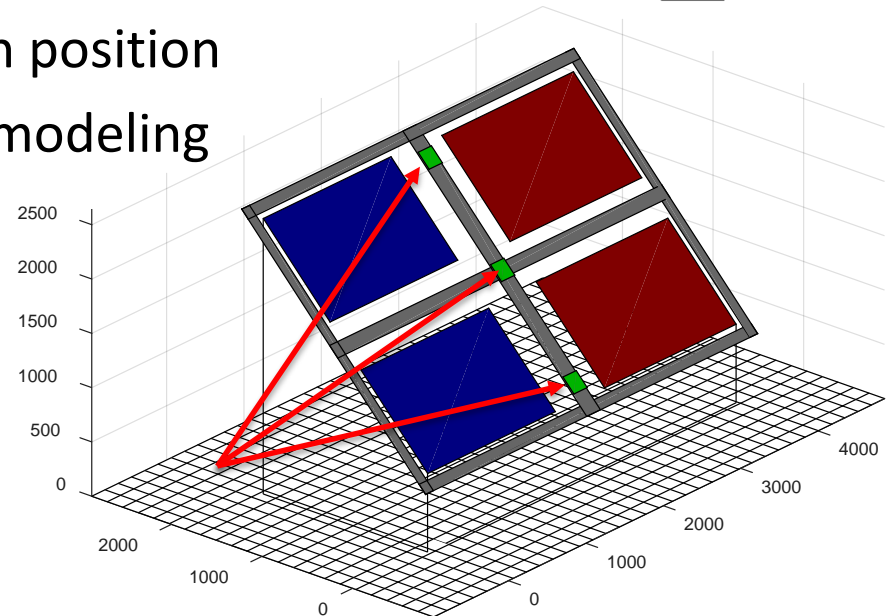
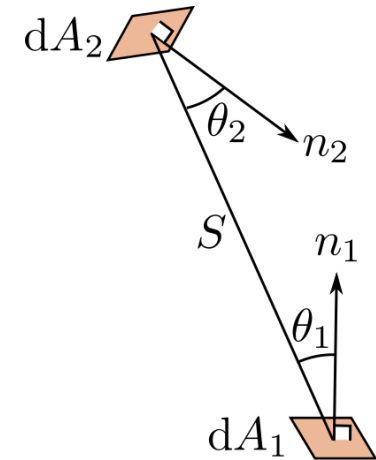


# Efficiently calculating view factors

- 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

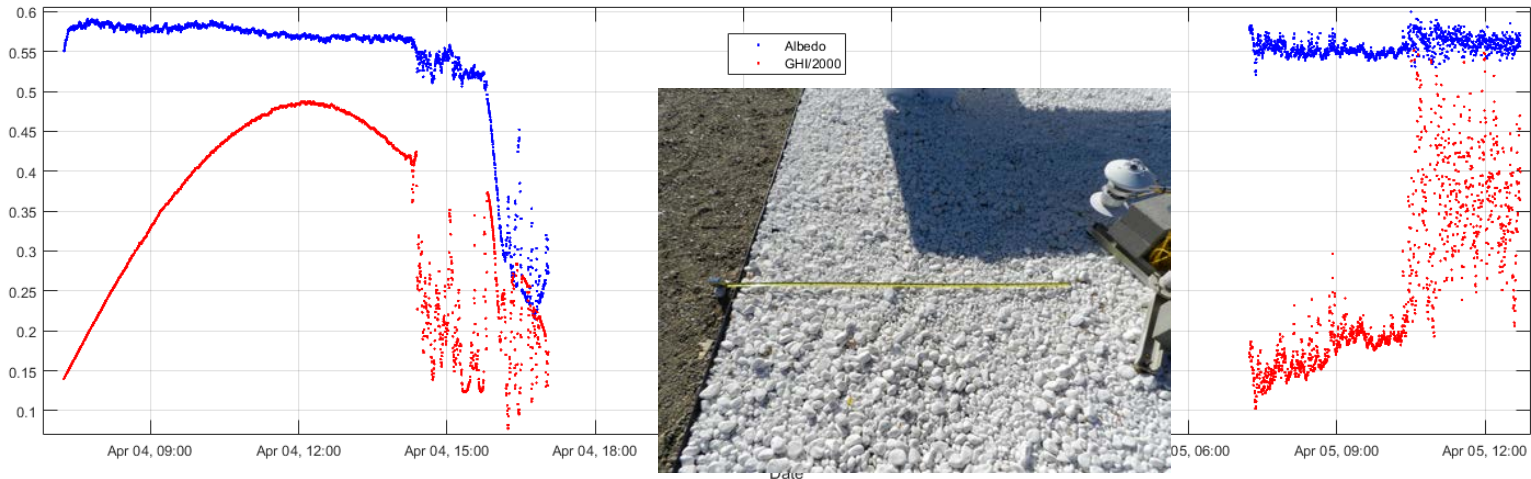


- Approximate integrals with value at centroids of each cell
- $\cos$  computed by matrix product
- Fast enough on CPU, anticipate x100 speedup expected on GPU

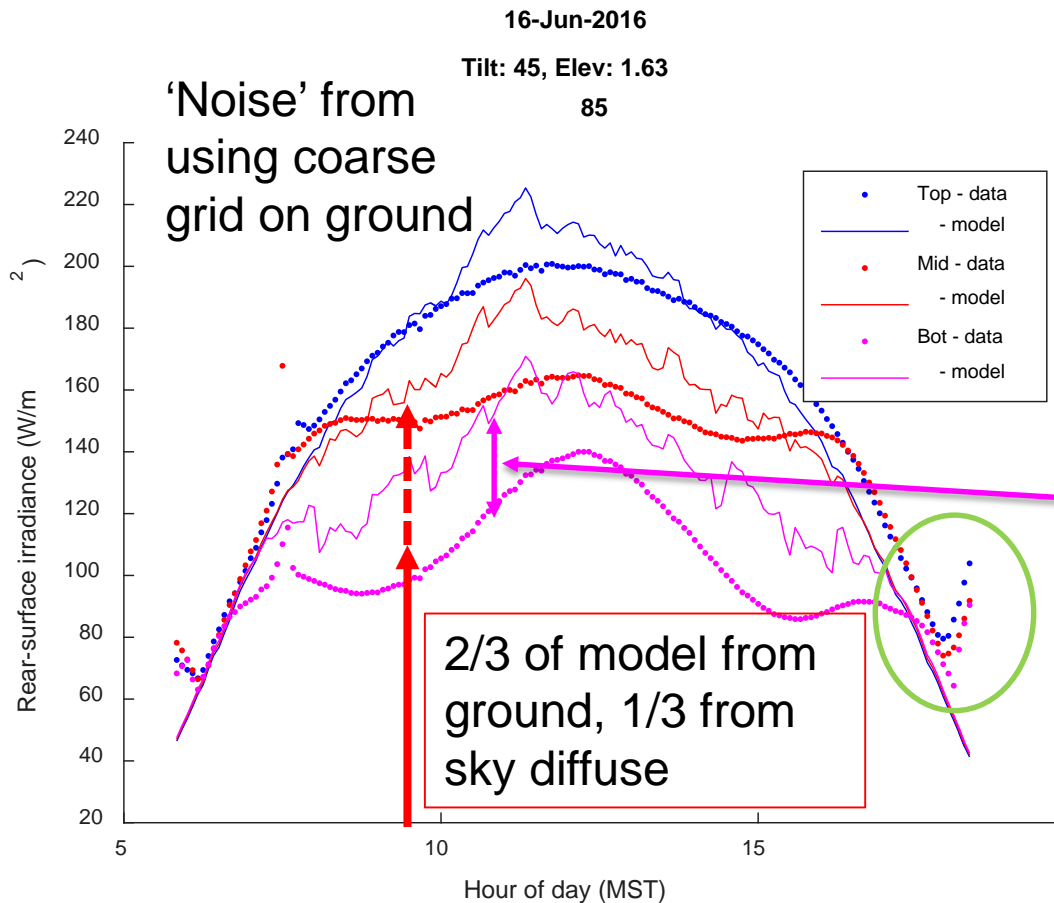
# Rear surface irradiance model

- $G$  (W/m<sup>2</sup>) 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

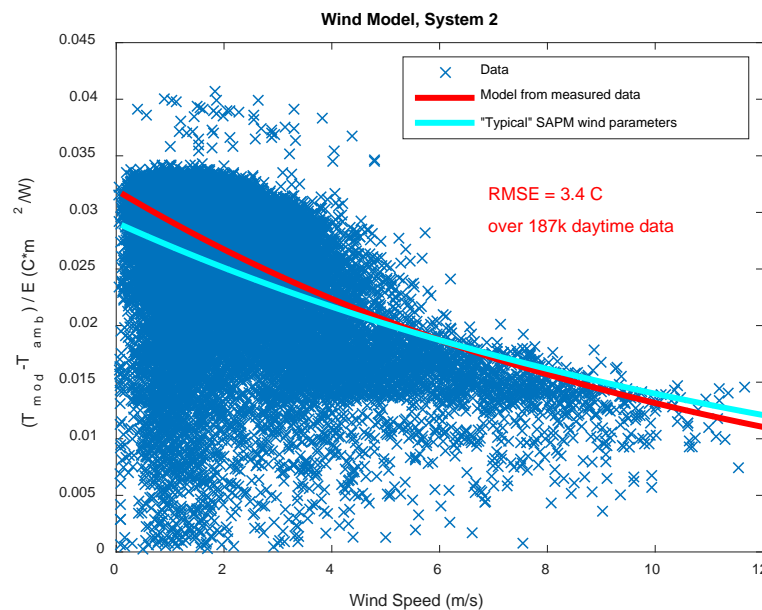
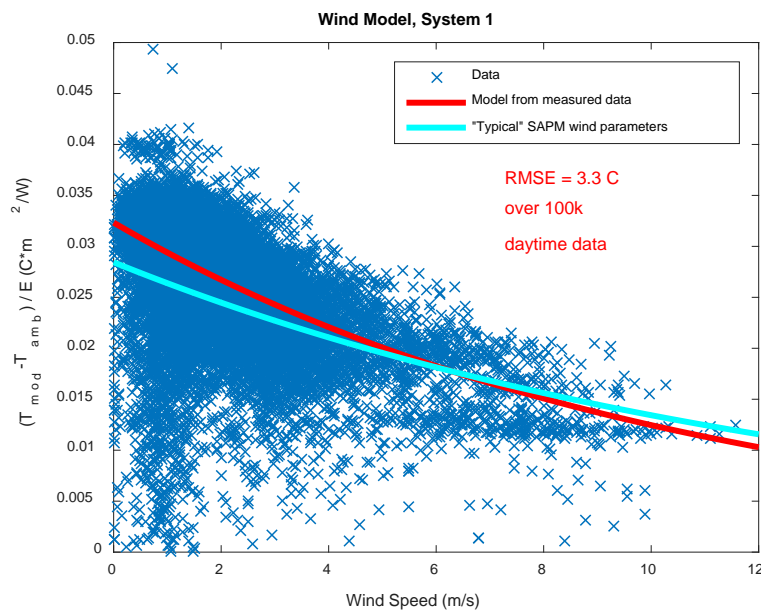
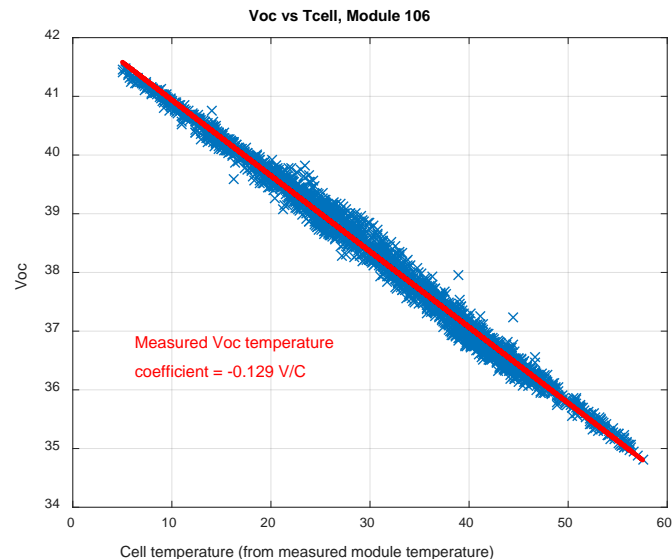


Overestimate - 'extra' diffuse from  $VF_{\text{cell to sky}} = 1$  ??

Direct light from sunrise and sunset behind array

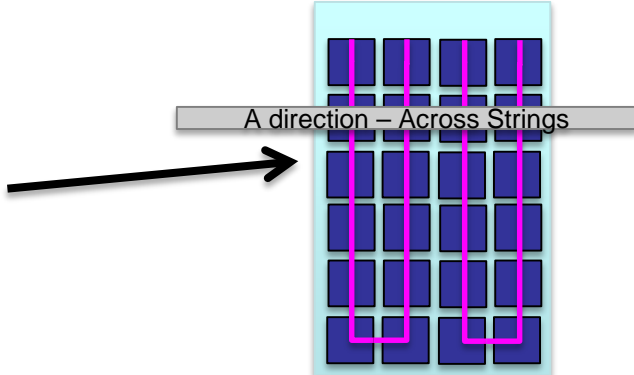
# Cell temperature model

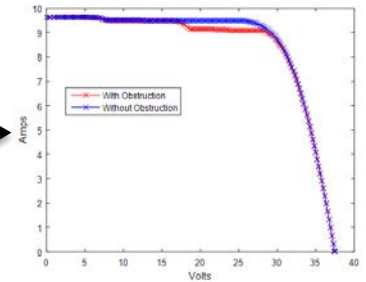
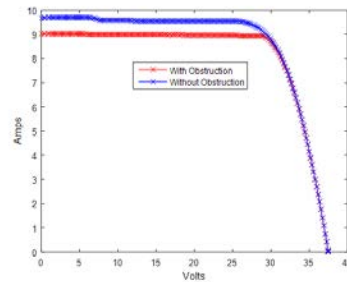
- For bifacial modules
  - Do  $V_{OC}$  and  $T_{cell}$  relationships still apply?
  - Can we still estimate  $T_{module}$  from environmental data such as  $E$ ,  $T_{ambient}$ , wind speed?



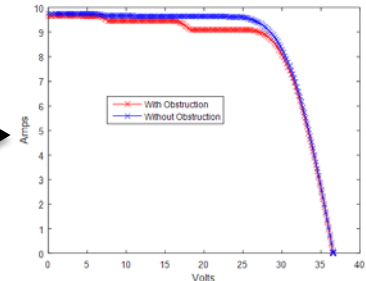
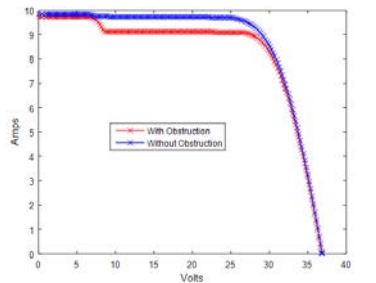


# Effects of rear-surface shading

- 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?



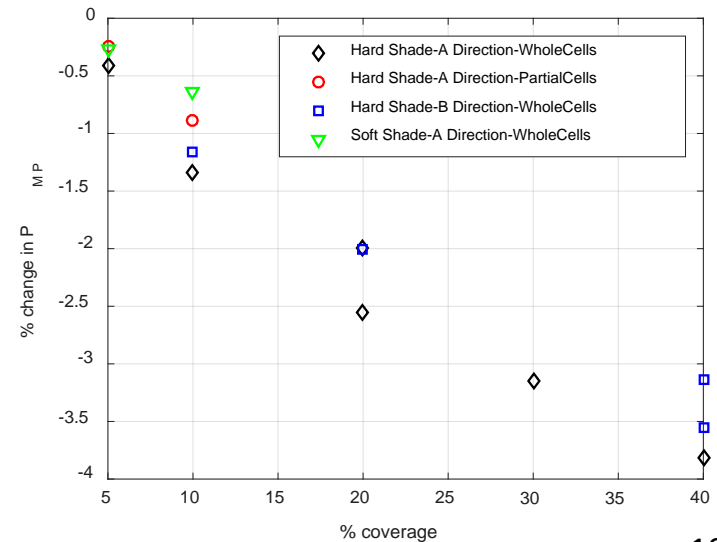
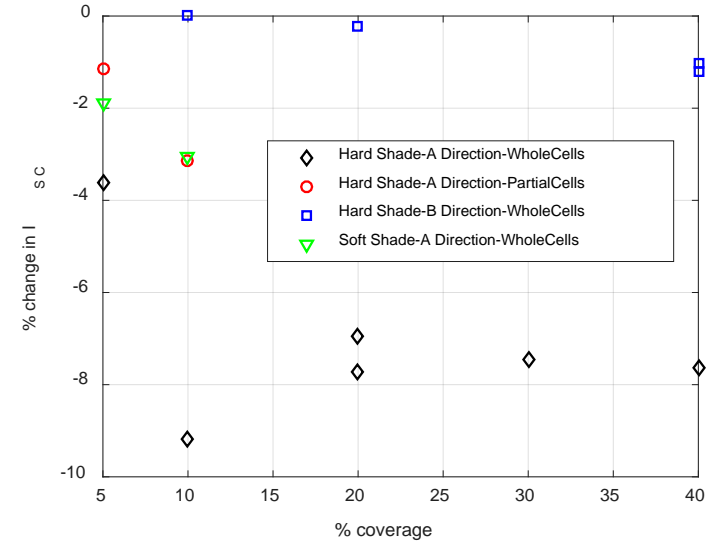
10% of active rear surface covered



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

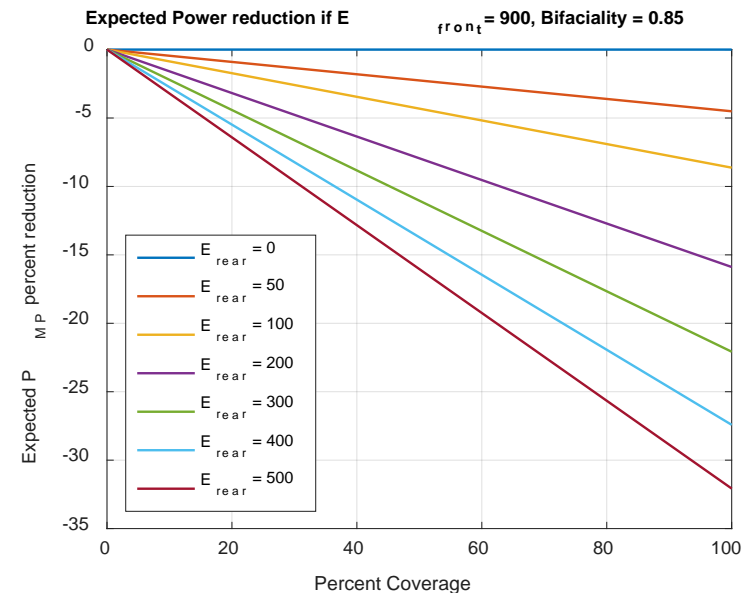


# Effects of rear-surface shading

- 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
  - $\text{Module Pmp} \sim \text{POA (front)} + \text{SF} \times \text{average(rear surface irradiance)}$
  - 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

