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A DETAILED PERFORMANCE MODEL FOR BIFACIAL PV MODULES

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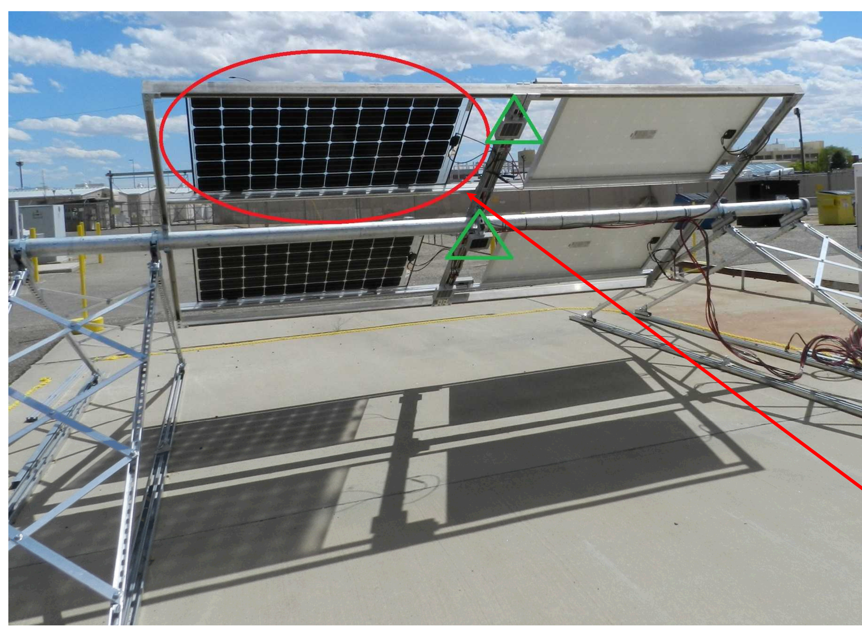
Purpose

We seek a performance model for bifacial PV modules to predict power over a wide range of irradiance and temperature conditions, and for a variety of module mounting and array designs. Our model employs configuration factors to compute irradiance the rear surface of each cell in the module, estimates cell temperatures from irradiance and ambient temperature, and predicts P_{MP}. Model performance is analyzed using measurements of bifacial module performance outdoors in Albuquerque, NM, USA.

Adjustable rack for measuring bifacial module performance at various tilts and heights.



Bifacial module under test (red circle) and rear-facing irradiance measurements with reference cells (green).

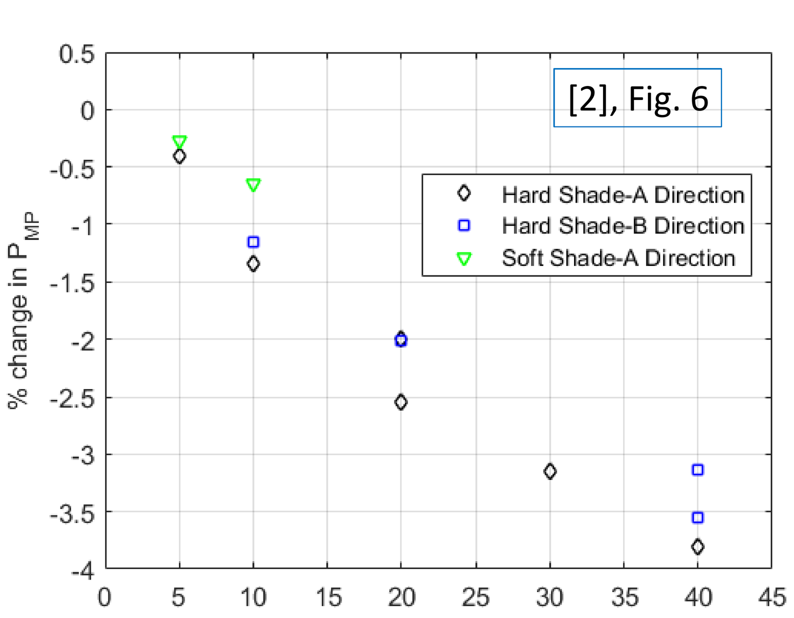
Components of the bifacial module performance model

The following components comprise our performance model for a bifacial module. Components unique to bifacial modules are highlighted.

- **Front irradiance** : broadband POA irradiance on the module's front is modeled as is done for monofacial PV modules.
- **Rear irradiance** : modeled cell by cell using a view factor approach [1].
- **Reflections, soiling and shading** :
  - Front surface: modeled as is done for monofacial PV modules.
  - Rear surface: reflections and soiling are not considered. Shading from array obstructions, e.g., racking, is modeled using a power derate.
- **Spectral response** :
  - Front surface : modeled as is done for monofacial PV modules.
  - Rear surface : not modeled.
- **Module and cell temperature** : modeled as is done for monofacial modules.
- **Electrical output** : modeled similar to PVWatts

Rear surface shading

Array structures, e.g., racking, wiring, ground mounting, can shade rear-facing cells from irradiance. PMP is generally proportional to shaded area; the proportionality depends on the distance between the structures and the module.

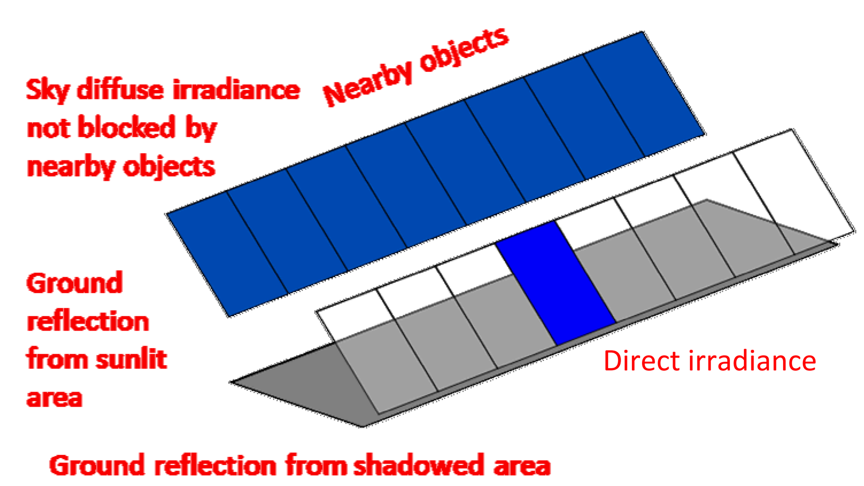


$$P_{MPo} = P_{MP}\left(1 - k_{obs} \times A_{obs} / A_{\mathrm{mod}}\right)$$

- P_{MPo} – power with obstructions
- P_{MP} – power without obstructions
- k_{obs} = 1 for obstructions against the module's rear surface, k_{obs} = 0.6 for obstructions a few cm away
- A_{obs} – total area of obstructions
- A_{mod} – module aperture area

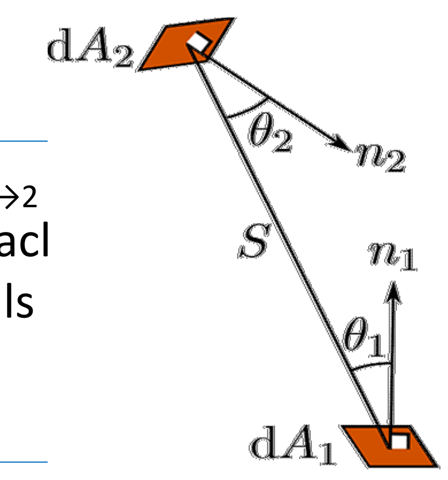
Rear irradiance modeling

We use the cell-by-cell view factor approach [1]. Variation in rear irradiance among cells is around 40 W/m^2 at midday.



Sources of irradiance on rear surface

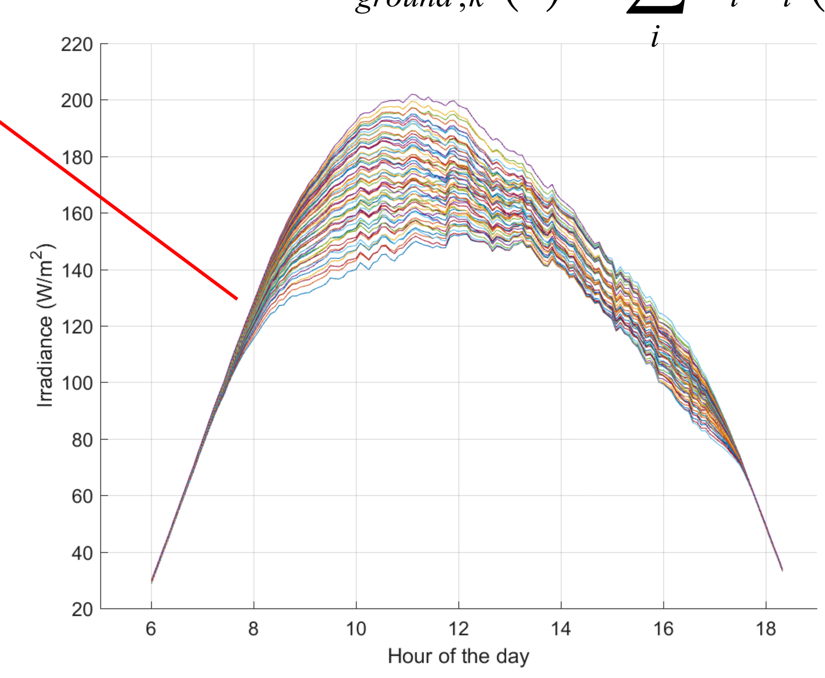
View factor $F_{1\rightarrow 2}$ computed for eacl pair of grid cells (module and ground)



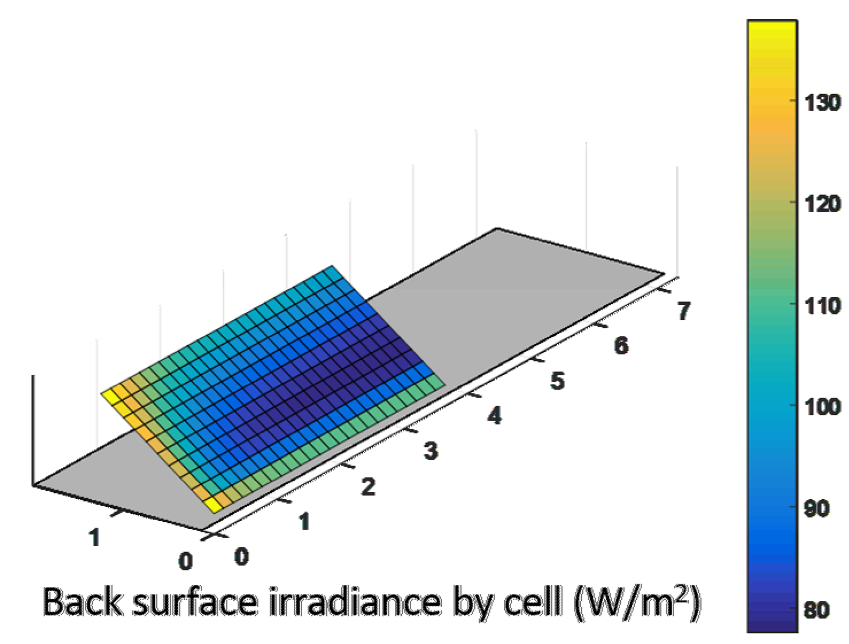
$$F_{1\rightarrow 2} = \frac{1}{A_1}\int_{A_1}\int_{A_2}\frac{\cos\theta_1\cos\theta_2}{\pi s^2}\, dA_2\, dA_1$$

$$E_{back,k}(t) = E_{ground,k}(t) + E_{sky}(t)VF_{k\rightarrow sky} + E_{beam}(t) \quad (3)$$

$$E_{ground,k}(t) = \sum_i \alpha_i G_i(t) VF_{i\rightarrow k} \quad (4)$$



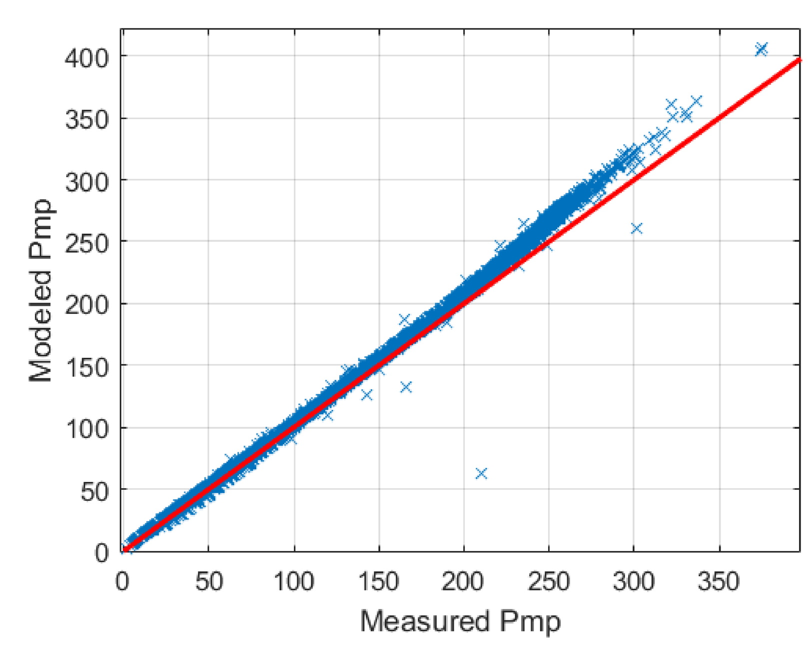
Cell-to-cell variation in rear surface irradiance: clear summer day in Albuquerque, NM



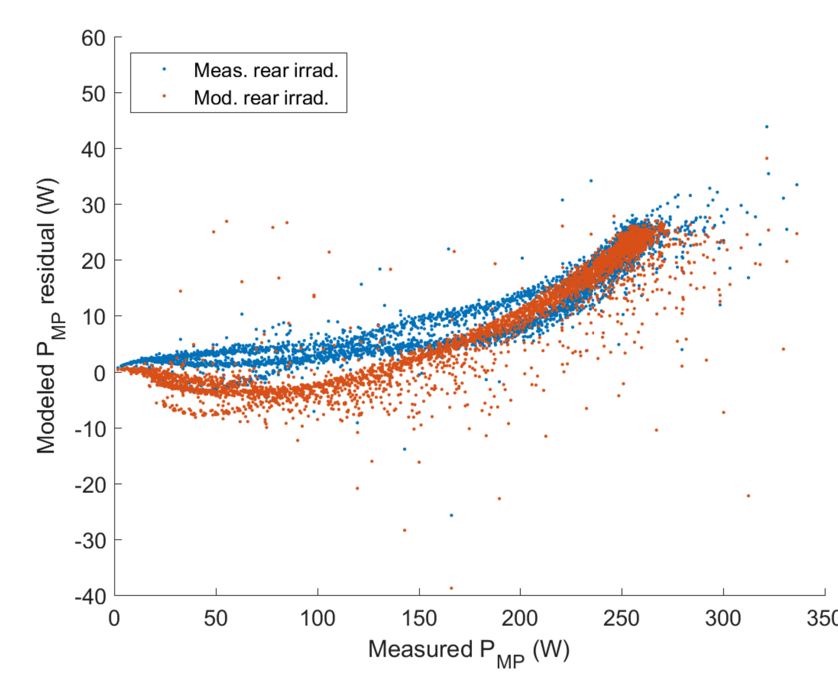
Modeled variation of rear surface irradiance along a notional row of modules on fixed tilt racking

P_{MP} model and results

$$P_{MP} = P_{MP0}\left(1+\gamma\left(T_C - T_0\right)\right) \quad \text{Cell temperature adjustment}$$
$$\times\left(M \times E_f + R_b \times E_r\right)/E_0 \quad \text{Response to total irradiance}$$
$$\times\left(1 - k_{obs} \times A_{obs}/A_{\mathrm{mod}}\right) \quad \text{Reduction for rear shading}$$



P_{MP} predicted from *measured* rear irradiance



P_{MP} prediction error for *measured* and *modeled* rear irradiance

Conclusions

- Model overestimates P_{MP} at high irradiance
  - Partially caused by cell-to-cell mismatch (not in model)
  - Possibly also due to module under test
- PMP predictions using cell-by-cell rear irradiance model are consistent with predictions using rear-facing reference cells

Next steps: incorporate mismatch
- Needed to predict I_{MP}, V_{MP} and I_{SC}

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References

[1] Hansen, C., et al (2017) *A Detailed Model of Rear-Side Irradiance for Bifacial PV Modules*, Proc. of 44th IEEE PVSC, Washington DC, USA.
[2] Riley, D., et al (2017) *A Performance Model for Bifacial PV Modules*, Proc. of 44th IEEE PVSC, Washington DC, USA.