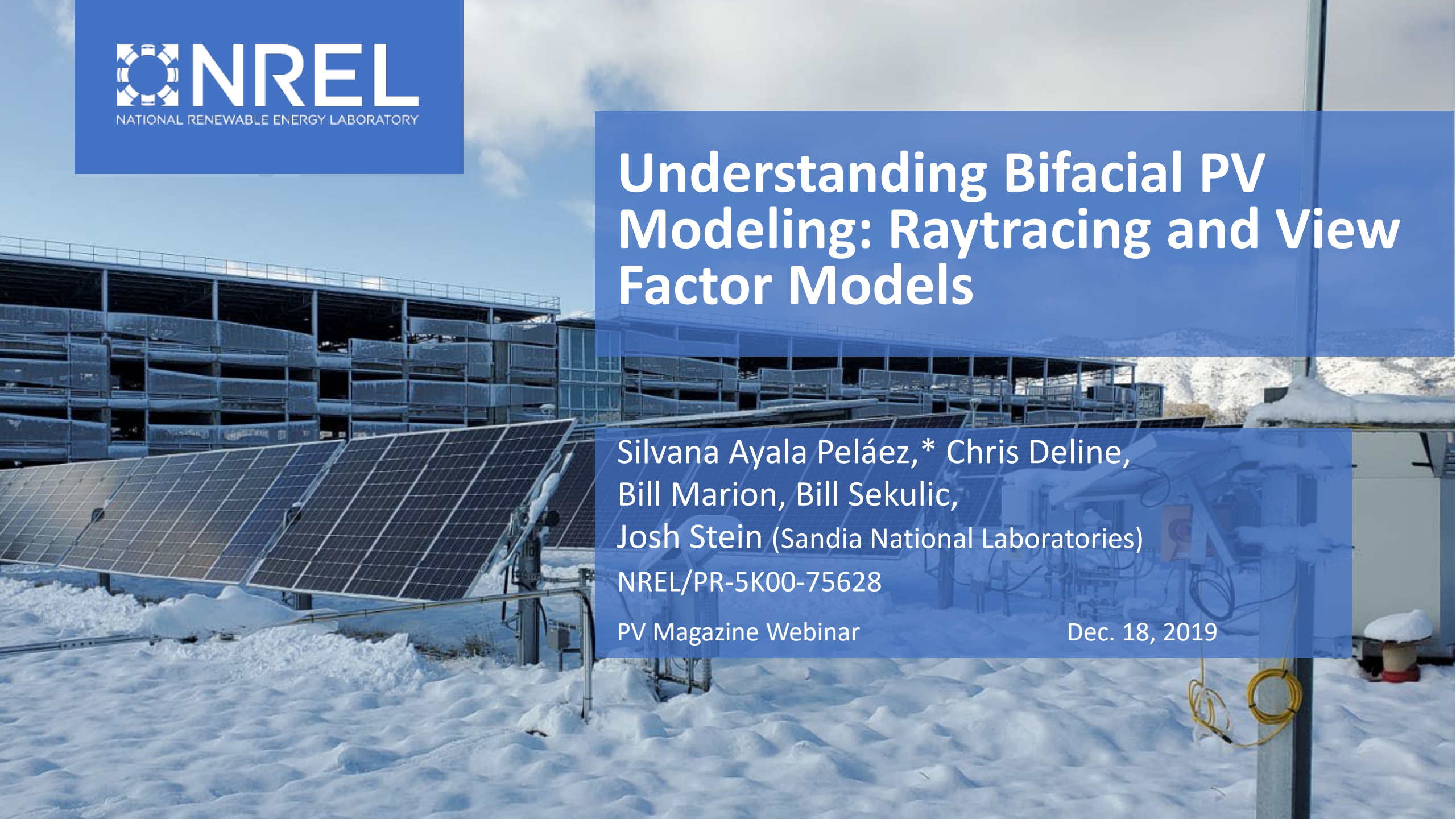


NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Understanding Bifacial PV Modeling: Raytracing and View Factor Models

Silvana Ayala Peláez,* Chris Deline,
Bill Marion, Bill Sekulic,
Josh Stein (Sandia National Laboratories)

NREL/PR-5K00-75628

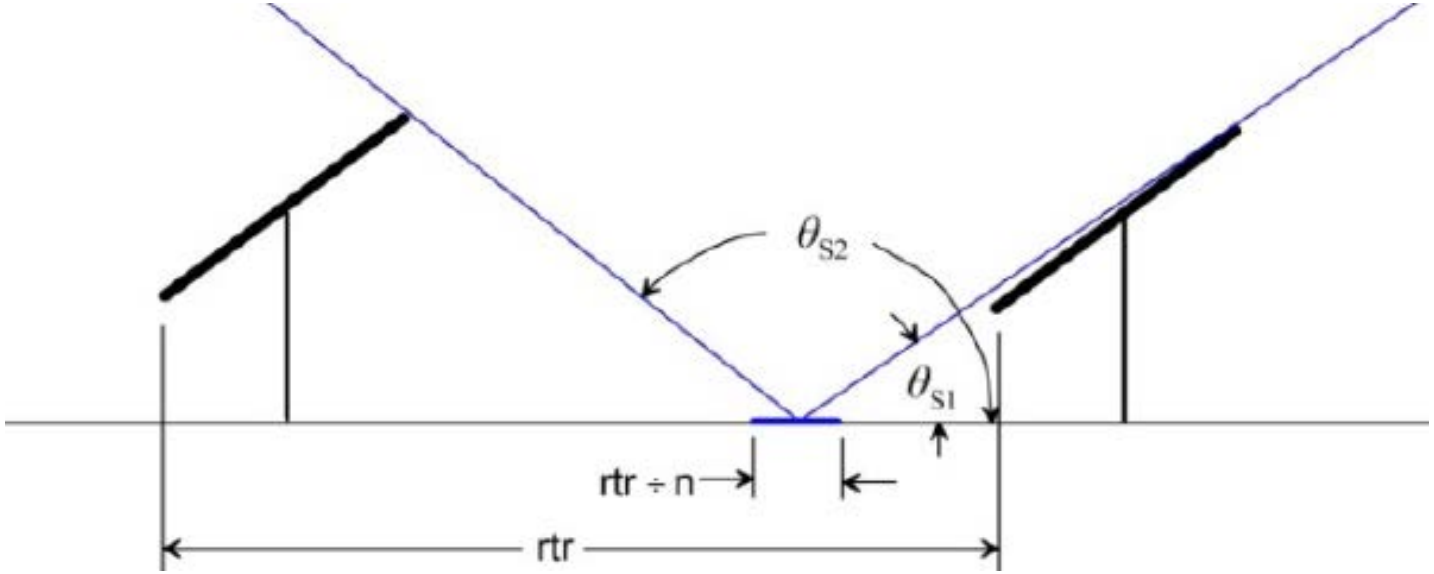
PV Magazine Webinar Dec. 18, 2019

Bifacial performance modeling

The PV industry is set for rapid uptake of bifacial PV if key barriers are eliminated

- accurate performance models,
- standards around the rating of bifacial modules, and
- accurate assessment of site albedo.
- documented bifacial gains in the field

View Factor Model for Rear Irradiance



Simple

basic **geometry**

Fast

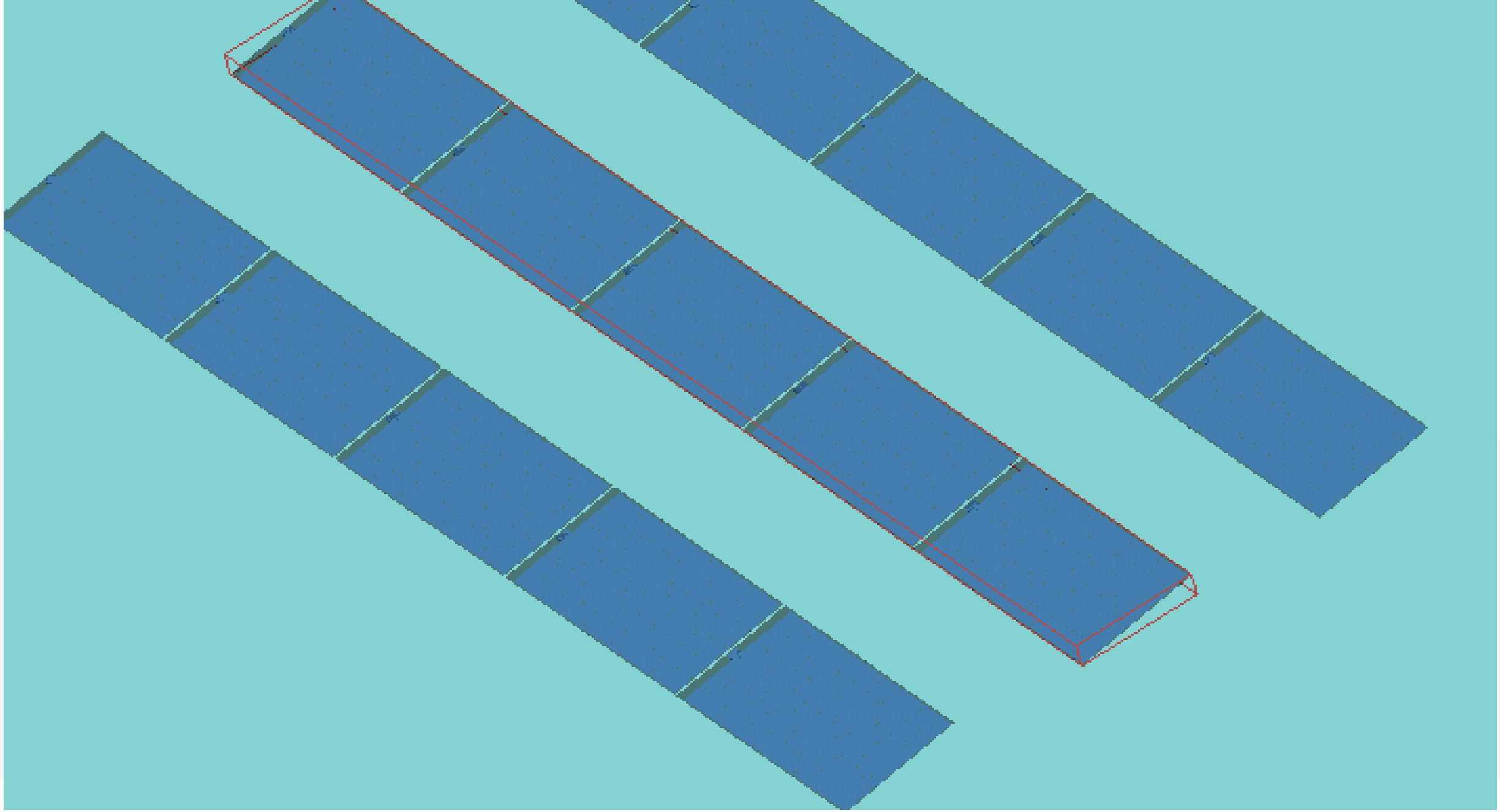
computationally **inexpensive**

Common

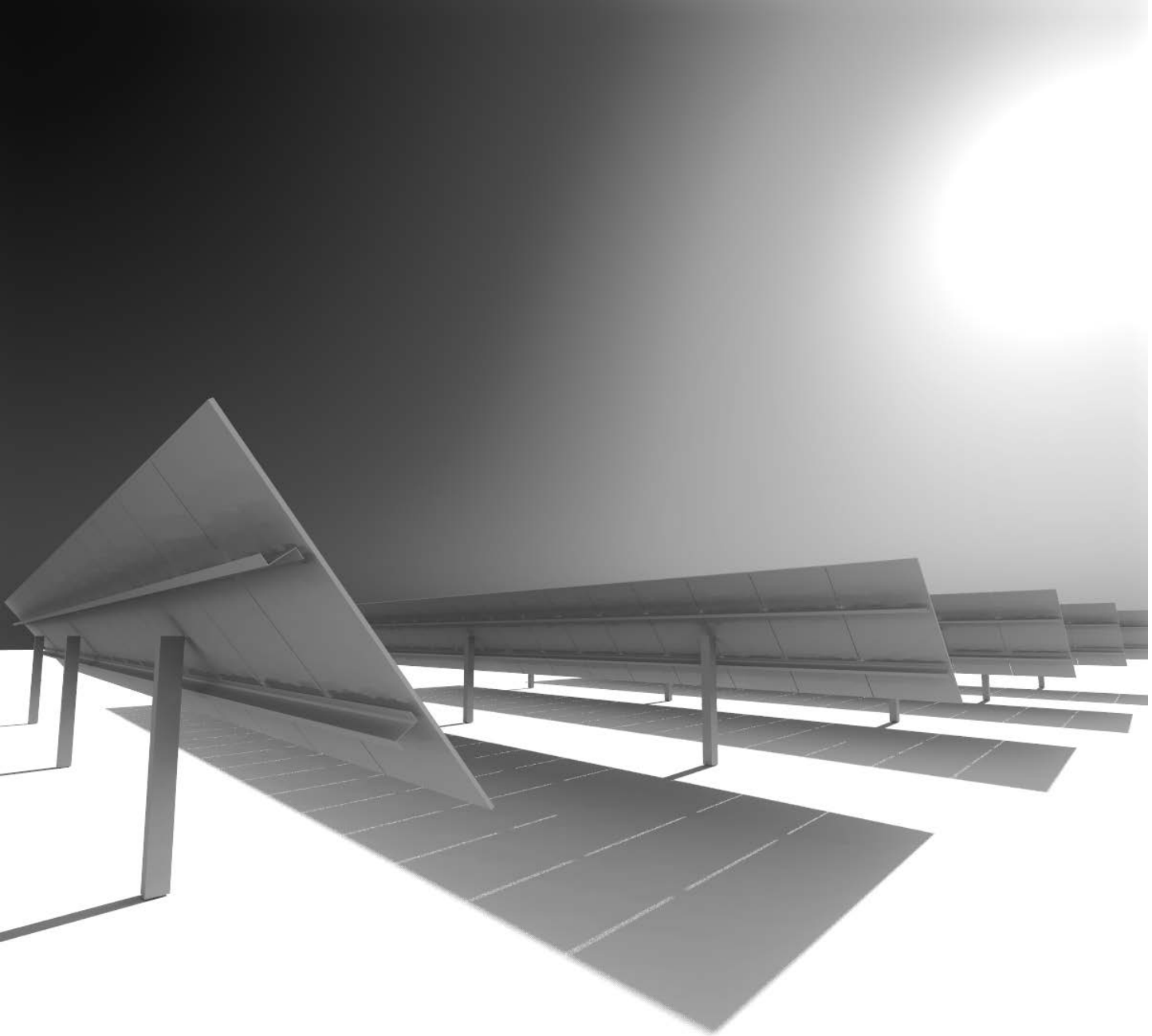
Behind SAM, PVSyst, bifacialvf and others

Simple

basic **geometry**



Other option: Raytracing Software



bifacial_radiance

Courtesy of Jason Alderman

Created with NREL bifacial_radiance https://github.com/NREL/bifacial_radiance

Raytrace benefits:

- Any size array
- Sample any module
- Evaluate edge effects
- Complicated geometries
  - Modules
  - Racking
  - Obstructions
- Evaluate shading
- Evaluate electrical mismatch
- Open source
- Dedicated visual interface
- Validated

Cons:

- Complexity ← Visual interface
- Run-times ← Training
  ← HPC integration
  ← Simplified models

PVSyst	Features	NREL VF / SAM	bifacial_radiance
✓	2D simulation of sheds	✓	✓ (3D, actually)
✓	Monthly albedo values	✓	✓
✗	Hourly/Instantaneous albedo values	✓	✓
✗	Circumsolar anisotropy for back side diffuse	✓ Perez model for rear irradiance, which includes circumsolar	✓
✗	IAM for backside reflections	✓ Apply IAM to both diffuse, reflected and direct-beam irradiance on the front and rear	▰
✓	Diffuse shading w/trackers	✓ / ▰	✓
▰	Irradiance non-uniformity	✓ / ▰	✓
✗	Spectral-corrected backside irradiance	✗	▰
✗	Specular reflections	✗	✓

Updated from Itai Suez, PV Performance & Reliability Workshop, Feb. 2019

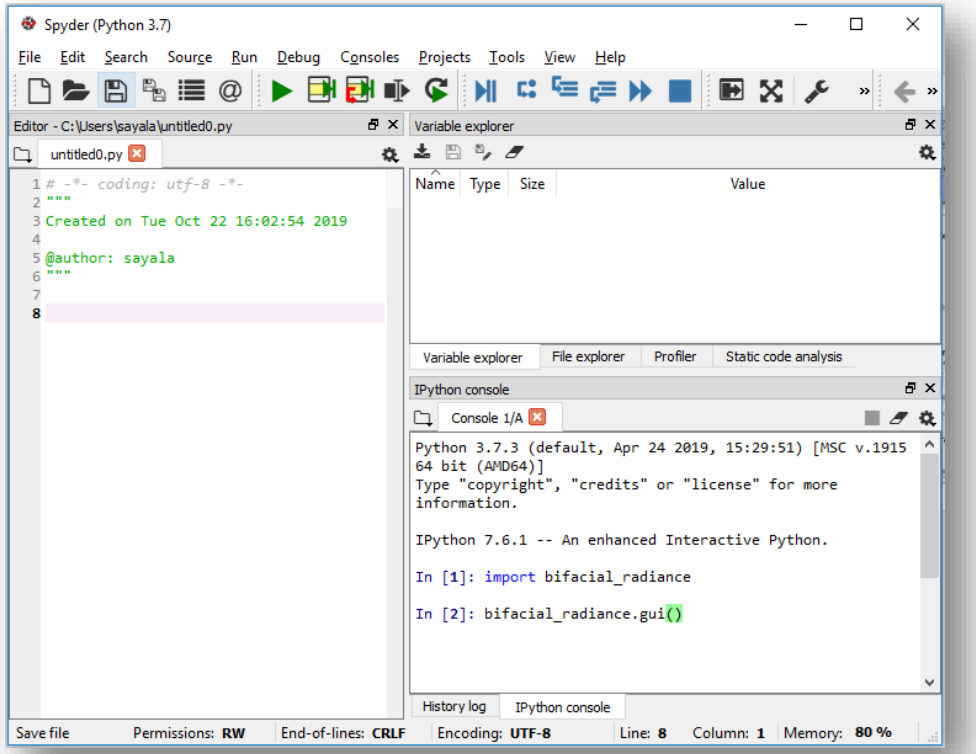
▰ Irradiance non-uniformity is addressed in PVSyst and SAM as part of the correction factors that can be applied to annual rear irradiance. SAM has a known issue with front-side diffuse shading in trackers deactivating for hours that have backtracking. Rear-side diffuse shading is still considered by the model. This issue is fixed in the beta version SAM Beta 2020.1.6 and future releases.
bifacial_radiance development branch considers IAM reflections for glass and is being modified for Spectrally-detailed simulations.

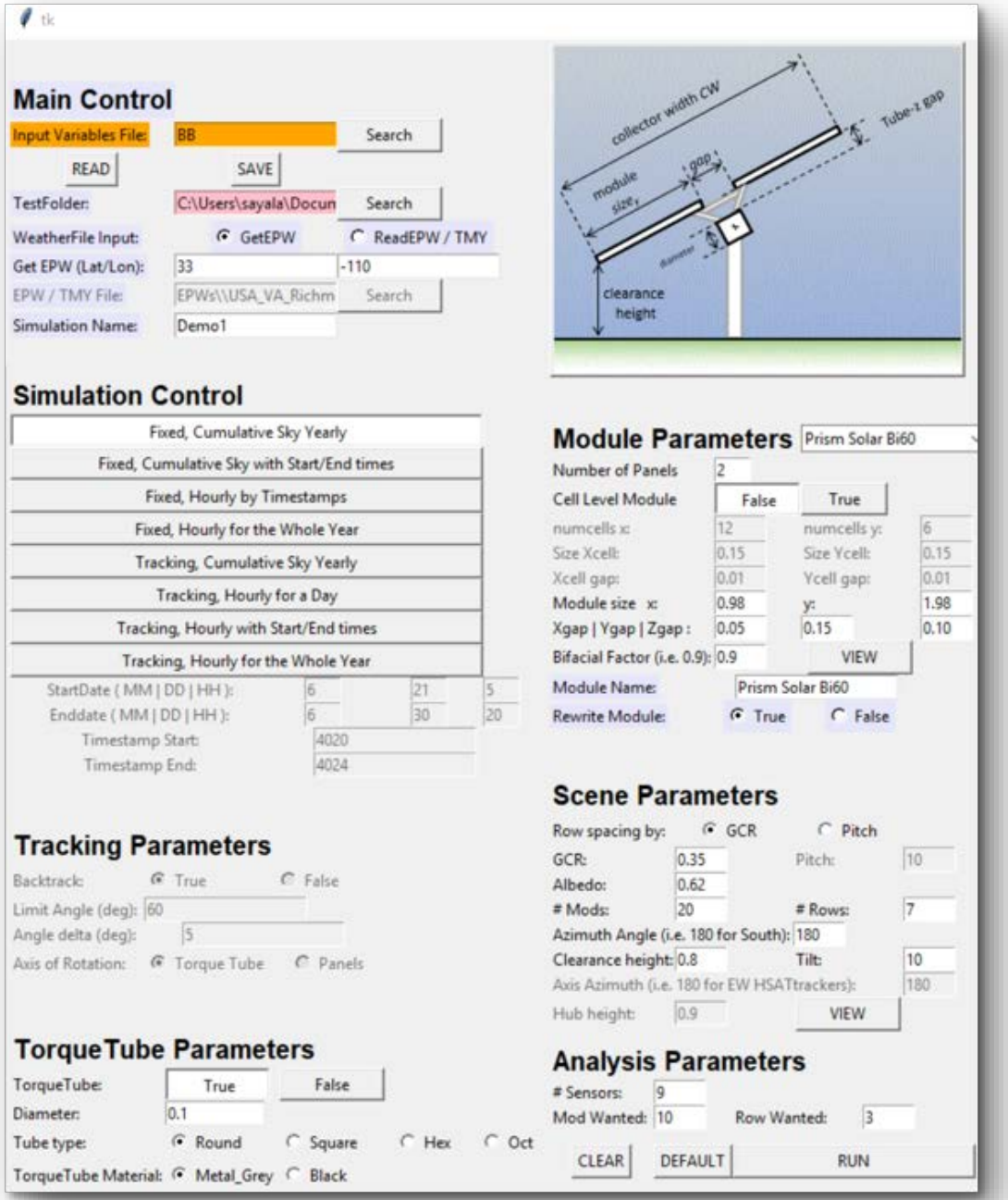
Open Source toolkit for working with RADIANCE for the ray-trace modeling of Bifacial Photovoltaics

Available on: https://github.com/NREL/bifacial_radiance
Documentation: https://bifacial-radiance.readthedocs.io
Installation: https://youtu.be/4A9GocfHKyM
Training: https://youtu.be/1X9L-R-RVGA | https://www.nrel.gov/docs/fy20osti/75218.pdf
V. 0.3.3.1 (10/16/19)

Python Interface

```
import bifacial_radiance
bifacial_radiance.gui()
```

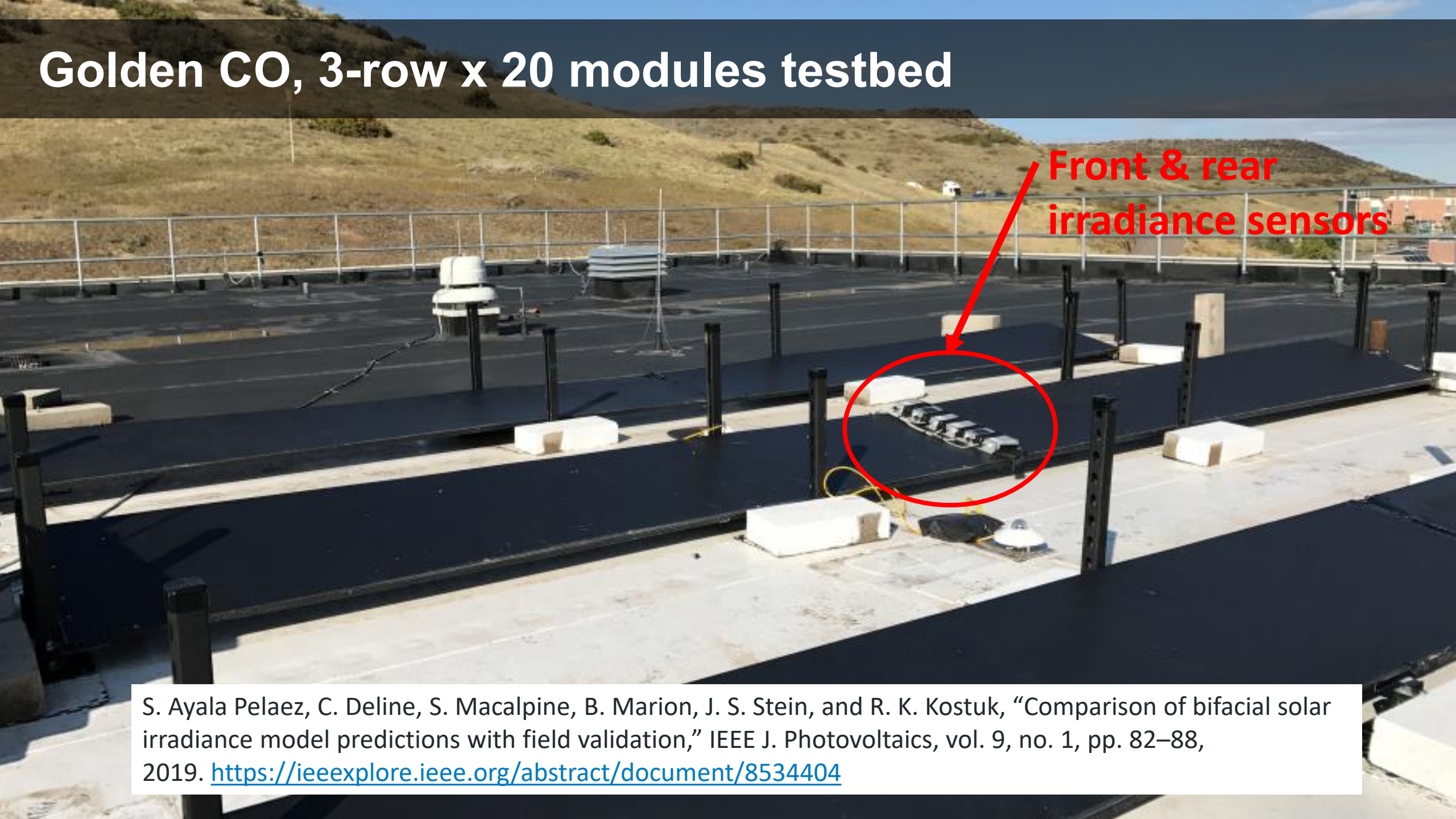




Looking at some details

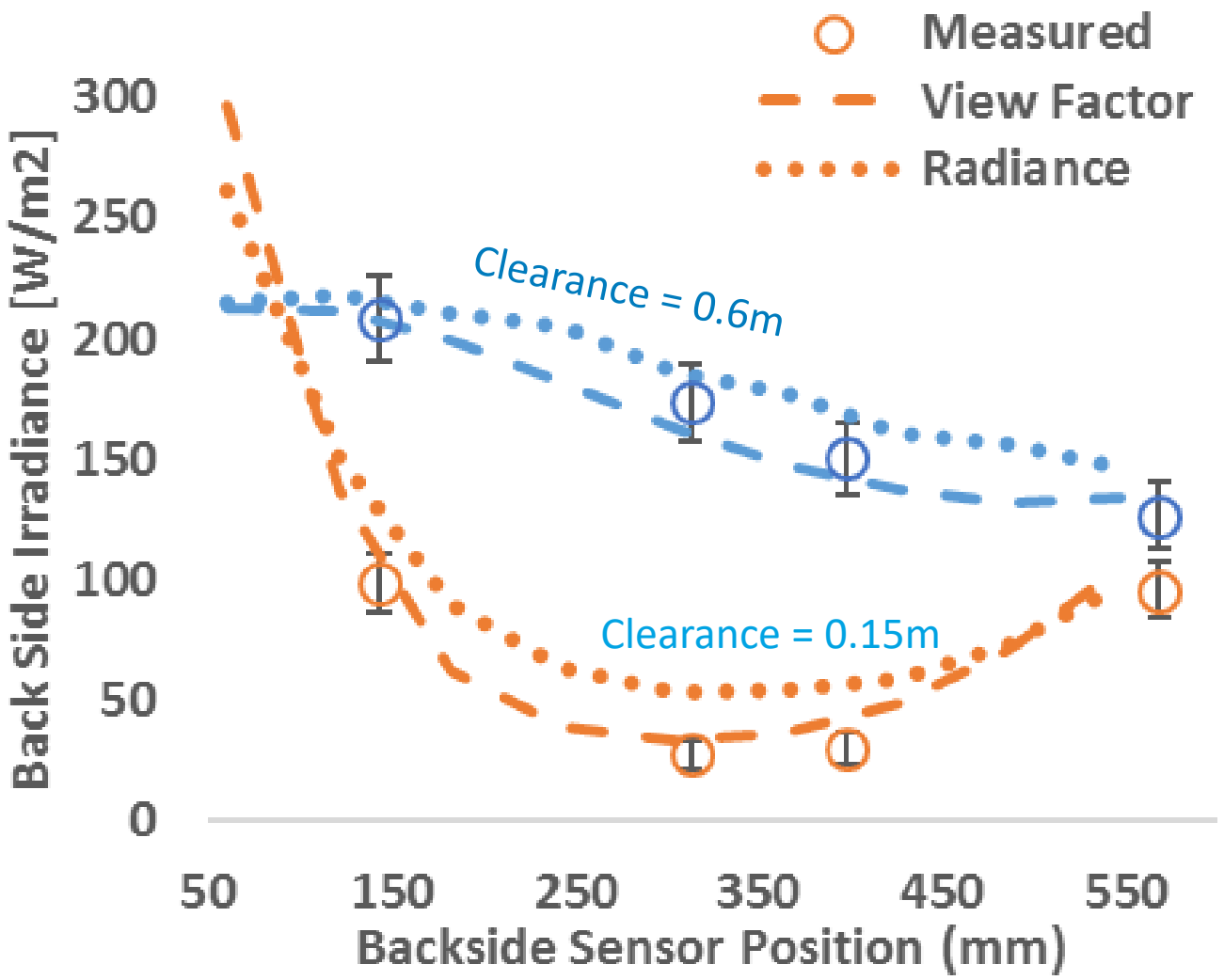
- Validation
- Size of array
- Edge effects
- Racking/tracking torque tubes

Golden CO, 3-row x 20 modules testbed



S. Ayala Pelaez, C. Deline, S. Macalpine, B. Marion, J. S. Stein, and R. K. Kostuk, “Comparison of bifacial solar irradiance model predictions with field validation,” IEEE J. Photovoltaics, vol. 9, no. 1, pp. 82–88, 2019. https://ieeexplore.ieee.org/abstract/document/8534404

Rear irradiance profiles for two noon hours



Testbed was modified for clearance, tilt, and row-to-row spacing.

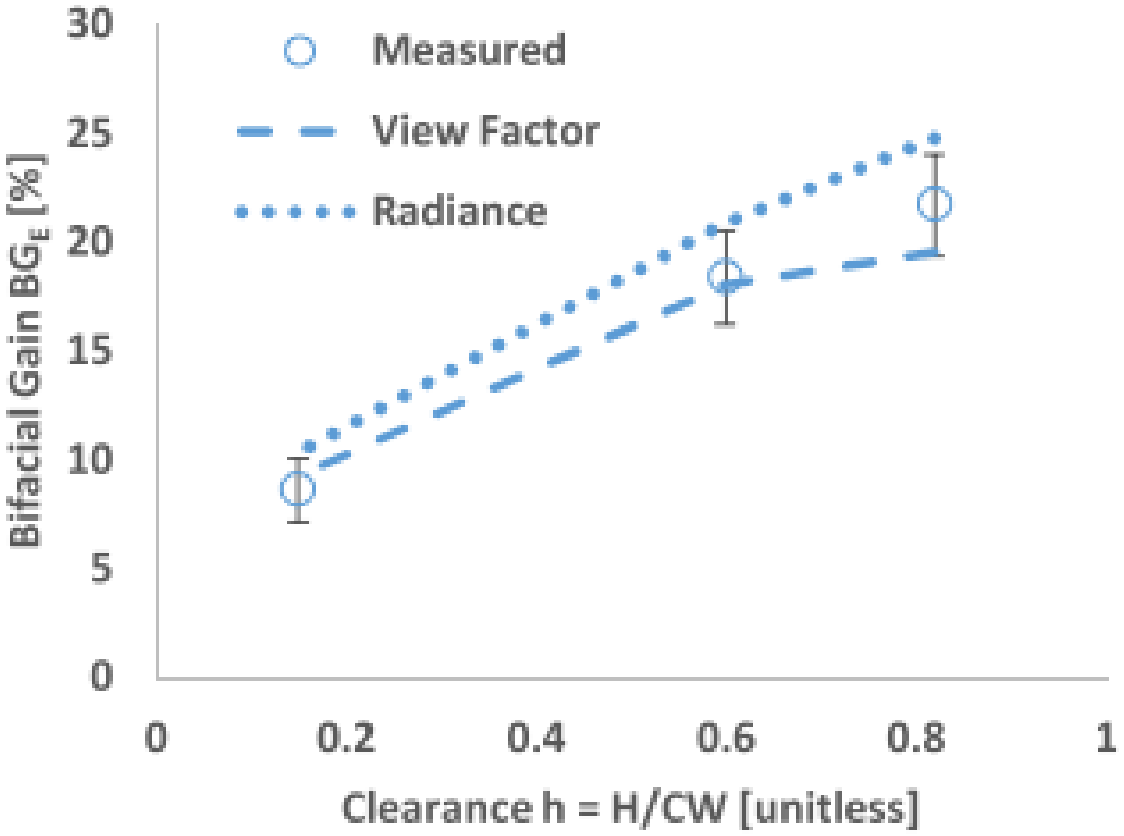
Data available by request, or check the resource below (awaiting release)

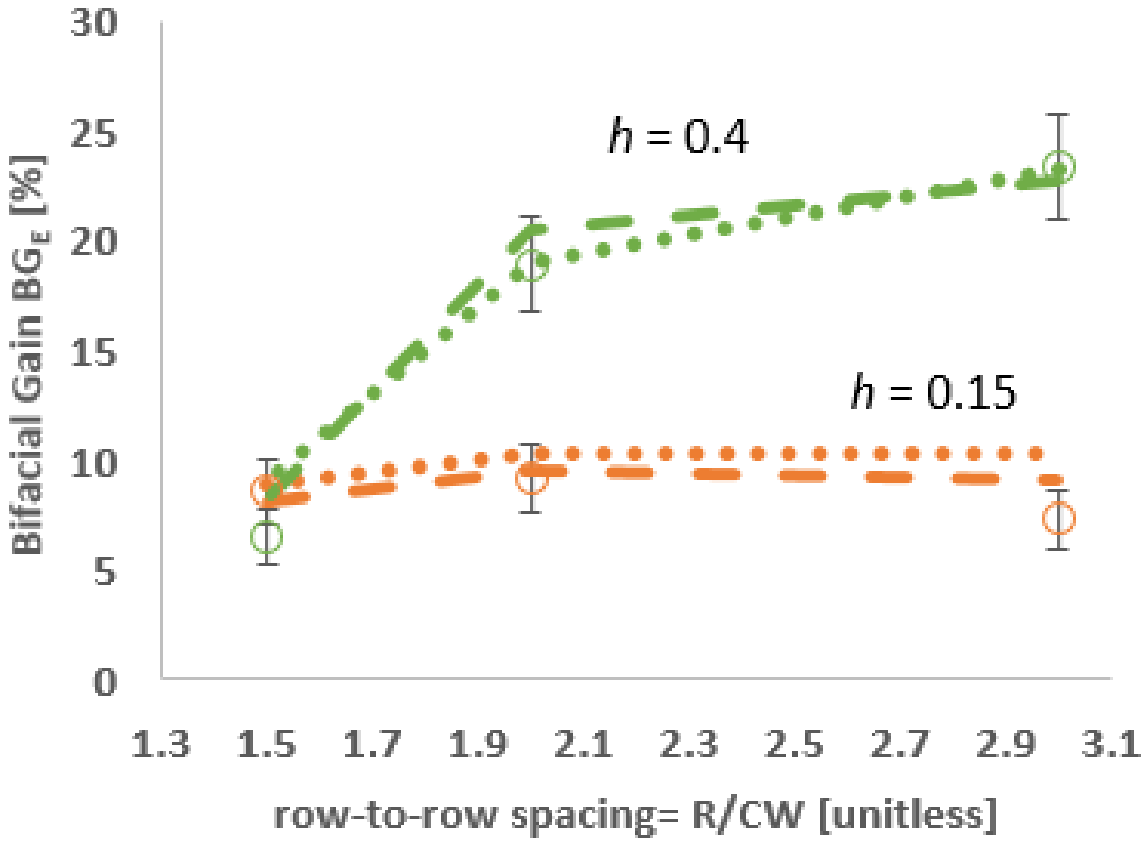
Ayala Pelaez, Silvana et al. (2019): Submission Name: Bifacial PV test-bed irradiance measurements. National Renewable Energy Laboratory. https://data.nrel.gov/submissions/125

S. Ayala Pelaez, C. Deline, S. Macalpine, B. Marion, J. S. Stein, and R. K. Kostuk, "Comparison of bifacial solar irradiance model predictions with field validation," IEEE J. Photovoltaics, vol. 9, no. 1, pp. 82–88, 2019. https://ieeexplore.ieee.org/abstract/document/8534404

Bifacial Gains Modeled vs. Measured

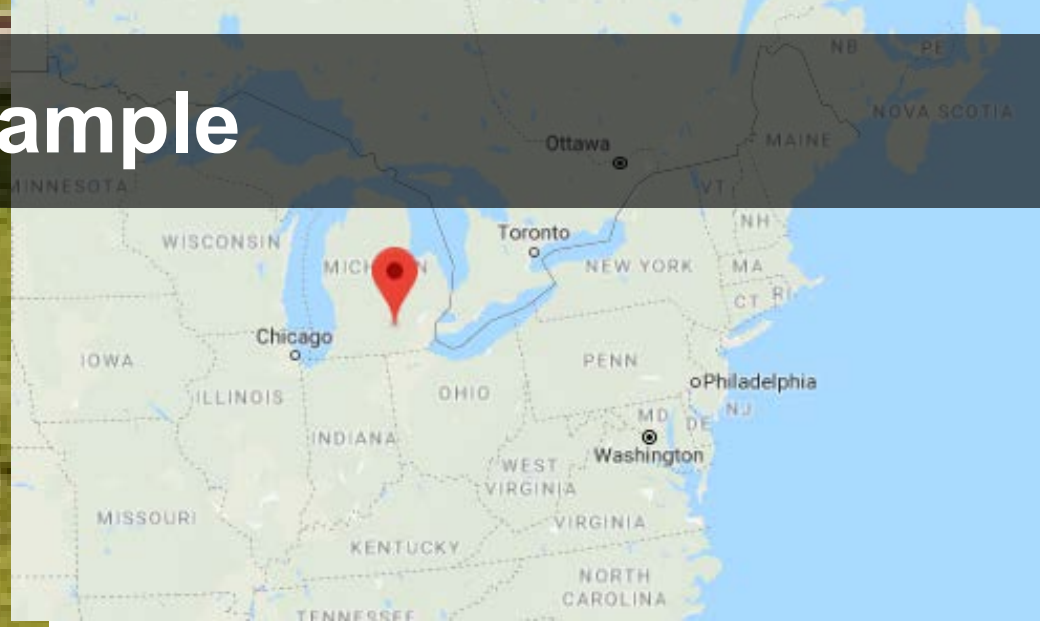
Each measurement is at least 2 weeks of data for each setup.





S. Ayala Pelaez, C. Deline, S. Macalpine, B. Marion, J. S. Stein, and R. K. Kostuk, "Comparison of bifacial solar irradiance model predictions with field validation," IEEE J. Photovoltaics, vol. 9, no. 1, pp. 82–88, 2019. https://ieeexplore.ieee.org/abstract/document/8534404

Jackson Michigan 1-axis tracker example



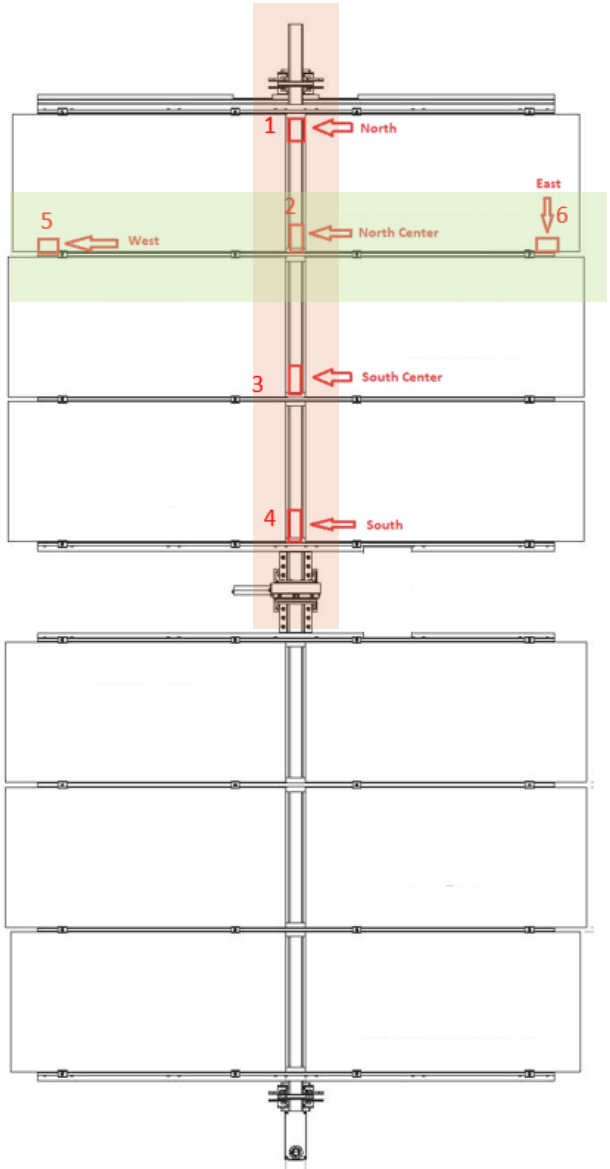
Ayala Pelaez, C. Deline, et al "Effect of torque-tube parameters on rear-irradiance and rear-shading loss for bifacial PV performance on 1-axis tracking systems". 46th PVSC Proceedings, Chicago 2019.
https://www.nrel.gov/docs/fy20osti/73203.pdf
Slides: https://www.nrel.gov/docs/fy19osti/74236.pdf

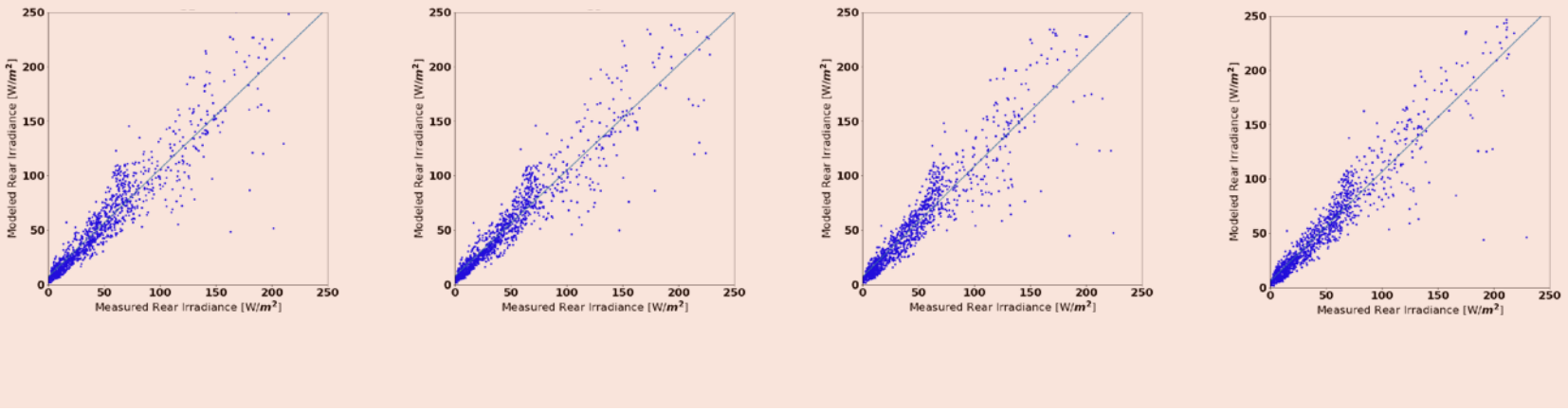
Rear irradiance at various positions on tracker

- Single row of HSAT, N-S oriented on Jackson, Michigan
- Data collected for 4 months, Dec. 2018 to April 2019.
- Albedo measured on location.

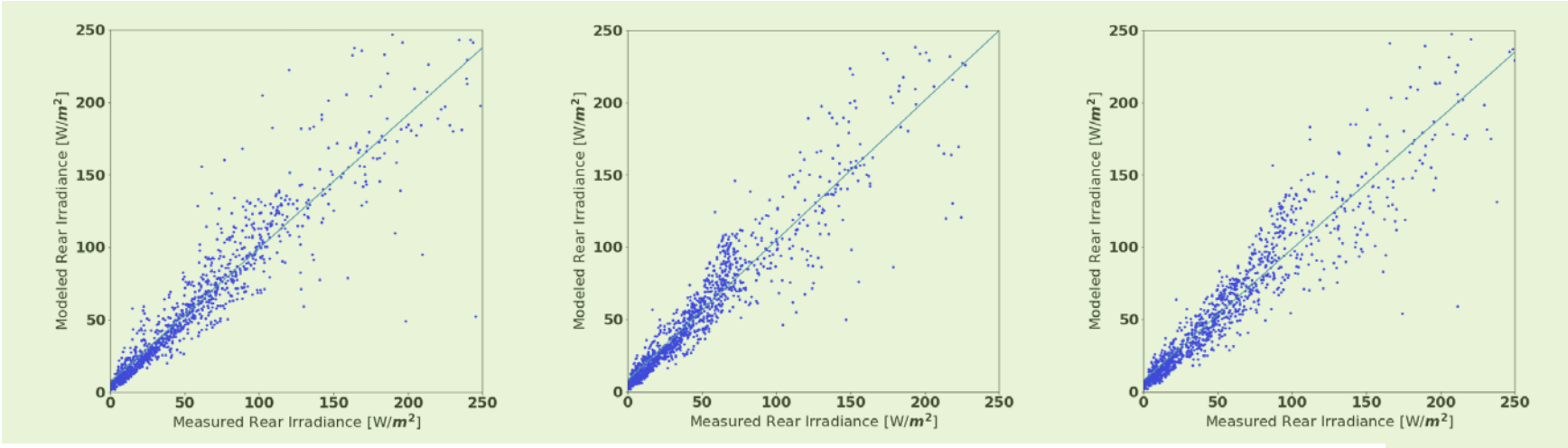
CYPRESS CREEK RENEWABLES

Measured vs. modeled Rear Irradiances





MBE 2.5-8 W/m² RMSE ~20 W/m²

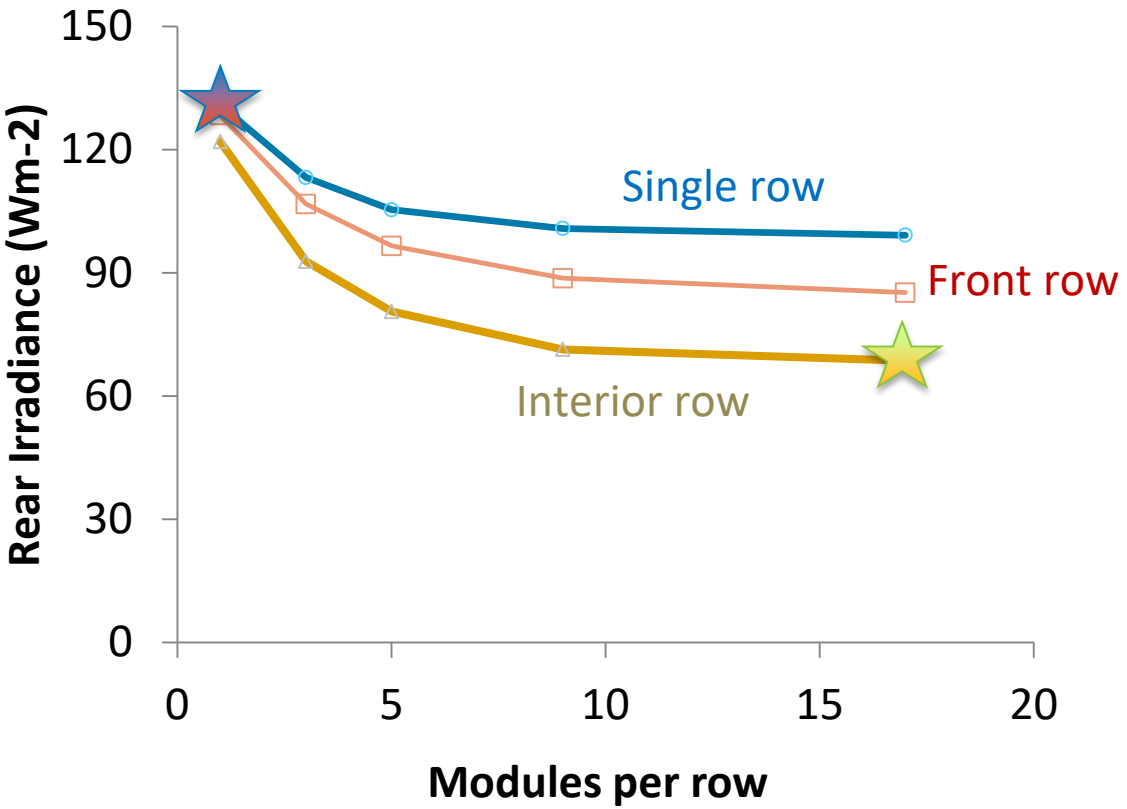


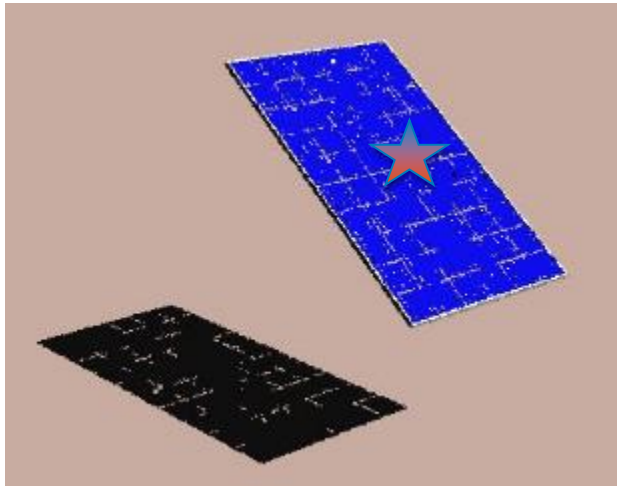
Ayala Pelaez, C. Deline, et al "Effect of torque-tube parameters on rear-irradiance and rear-shading loss for bifacial PV performance on 1-axis tracking systems". 46th PVSC Proceedings, Chicago 2019. https://www.nrel.gov/docs/fy20osti/73203.pdf Slides: https://www.nrel.gov/docs/fy19osti/74236.pdf

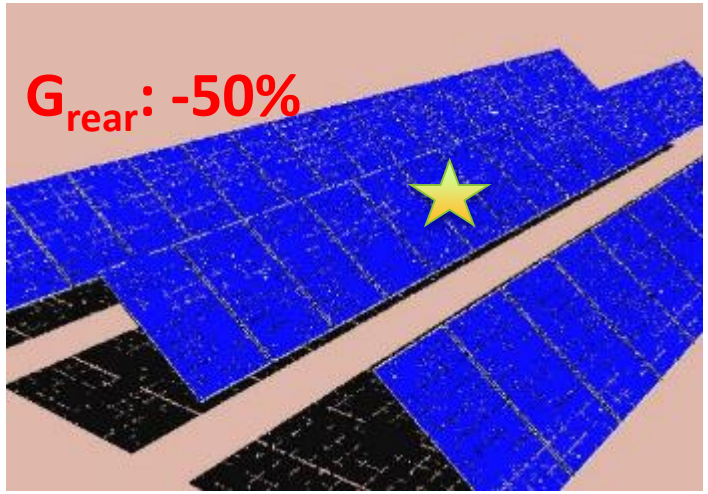
Looking at some details

- Validation
- Size of array
- Edge Effects
- Racking/tracking torque tubes

System Experiences Self-Shading







'Steady state': ~
7 rows x 10 modules

Fixed tilt systems:

C. Deline et al., "Assessment of bifacial photovoltaic module power rating methodologies – Inside and out," *J. Photovoltaics* **7** (2017).

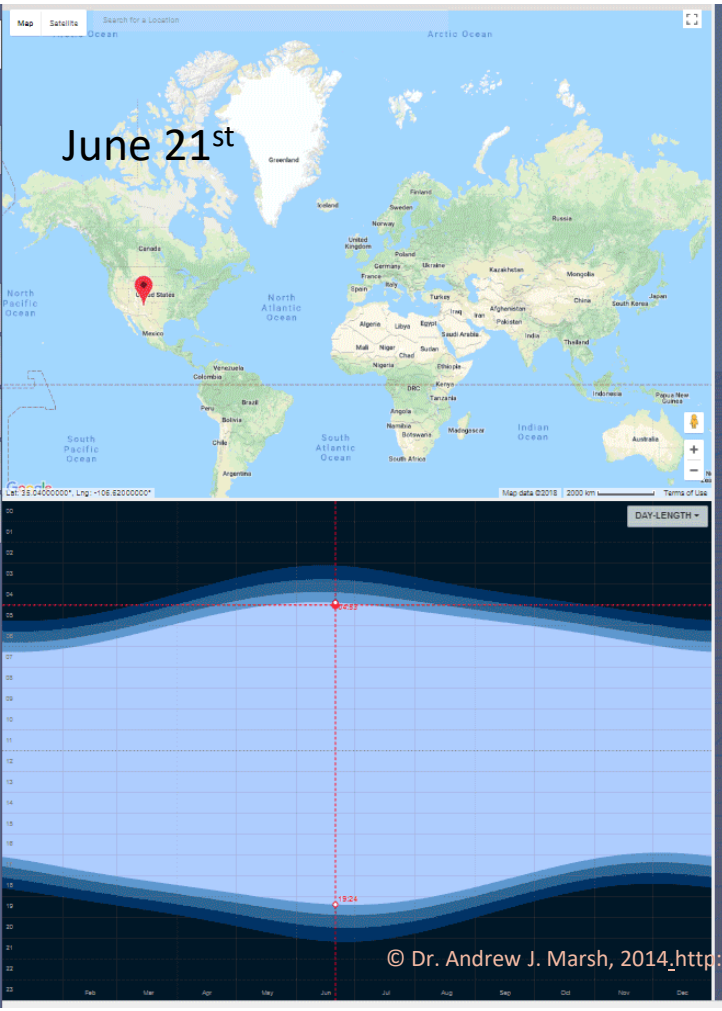
Tracked Systems:

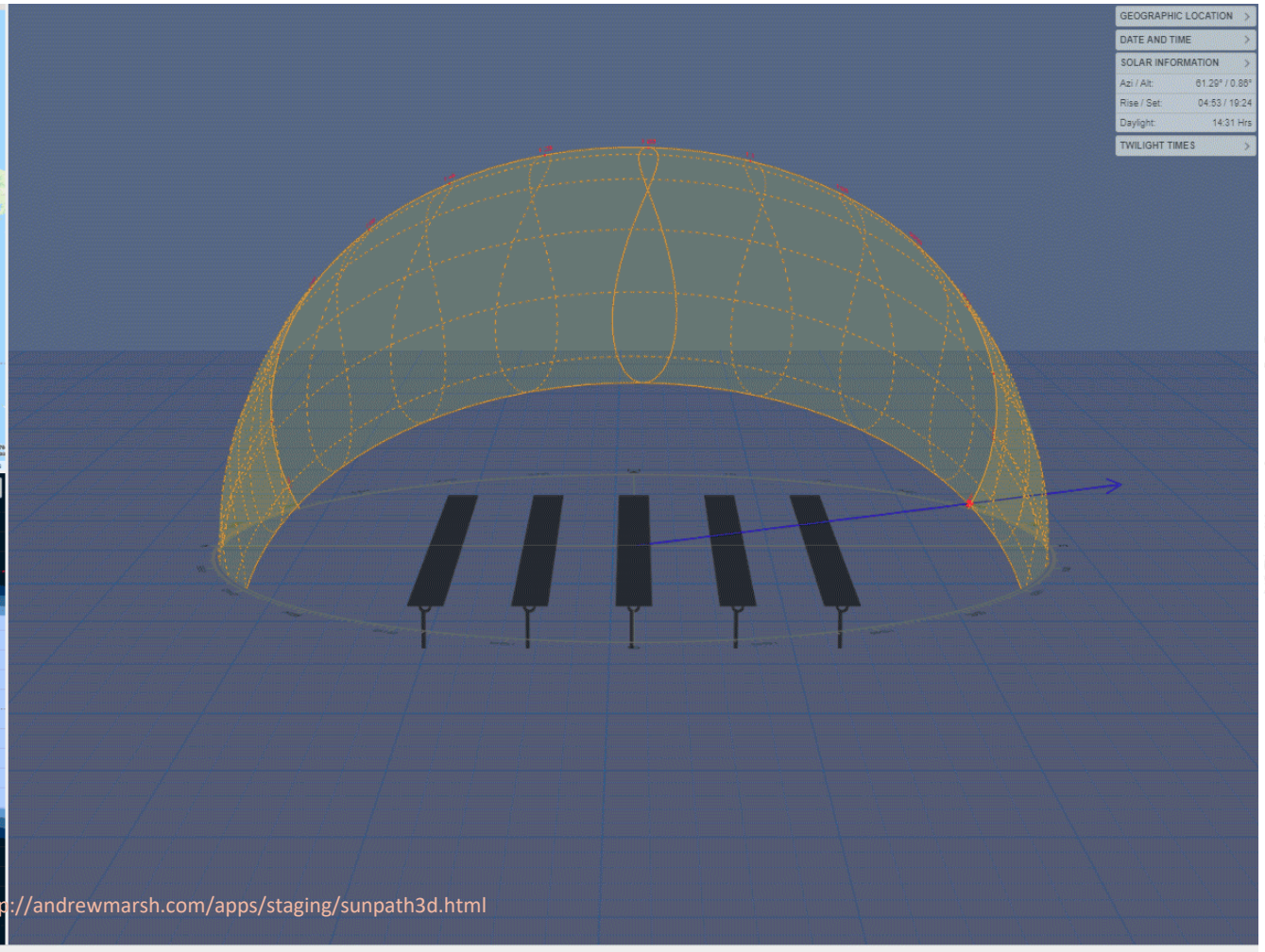
S. Ayala Pelaez, C. Deline, et al P. Greenberg, J. S. Stein, and R. K. Kostuk, "Model and Validation of Single-Axis Tracking with Bifacial PV", IEEE J. Photovoltaics, vol. 9, no. 3, 2019. https://ieeexplore.ieee.org/abstract/document/8644027. Pre-print version: https://www.nrel.gov/docs/fy19osti/72039.pdf

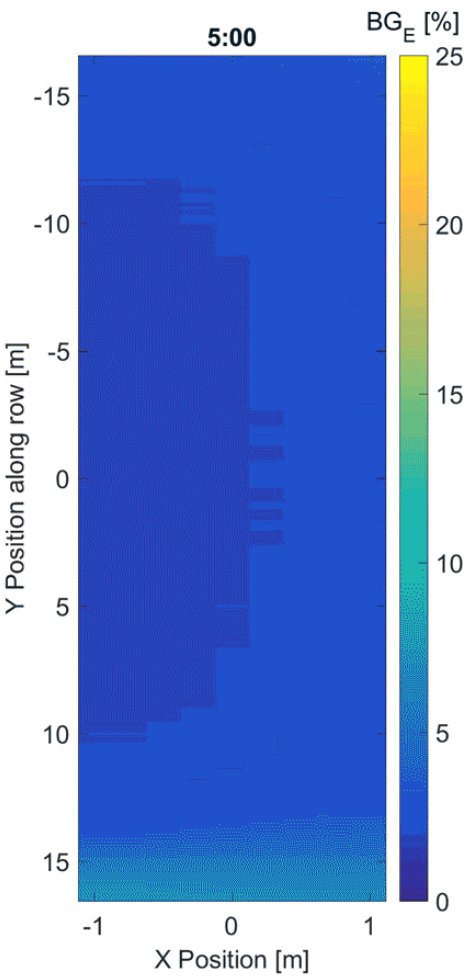
Looking at some details

- Validation
- Size of array
- Edge Effects
- Racking/tracking torque tubes

Hourly Bifacial gain in irradiance







Ayala Pelaez, Silvana, et al. "Model and Validation of Single-Axis Tracking With Bifacial PV." *IEEE Journal of Photovoltaics*(2019).

Other Ray-tracers:

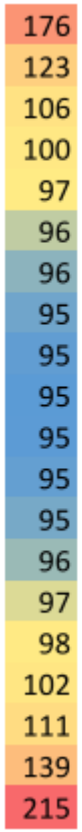


Figure 14 (left): Mapping of the rear irradiances received on the HSAT installation, GCR=63% [kWh/m²/year]

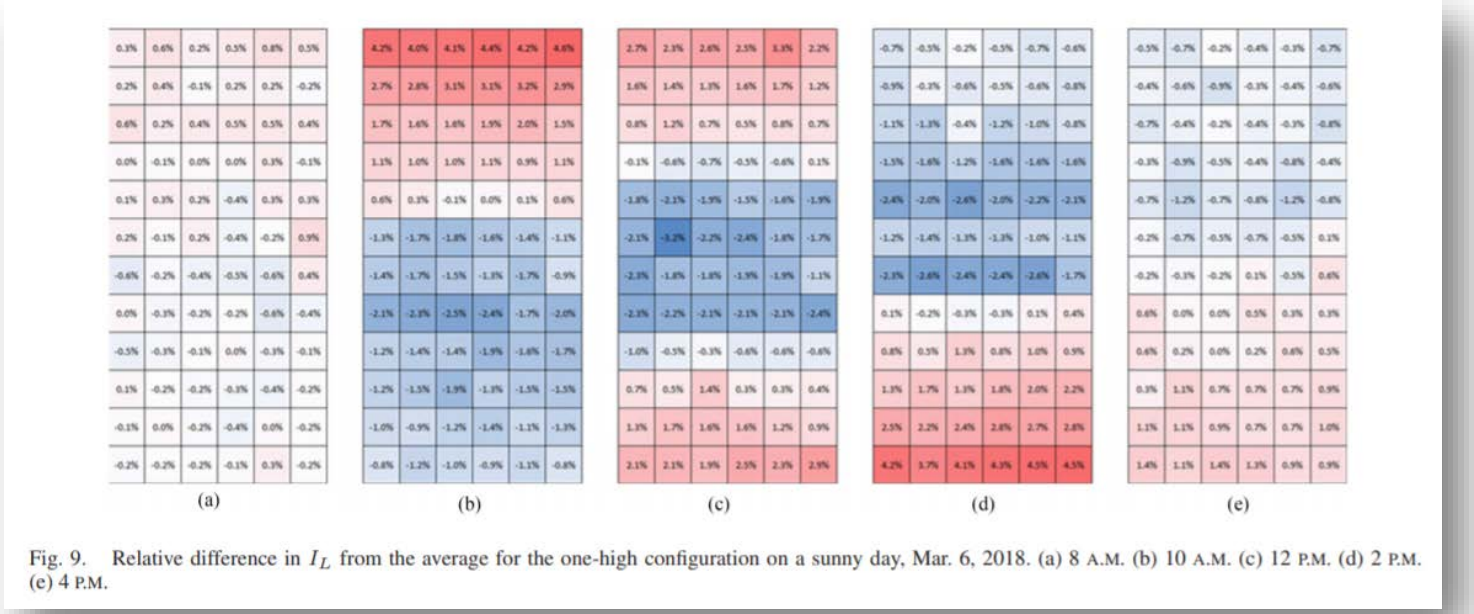
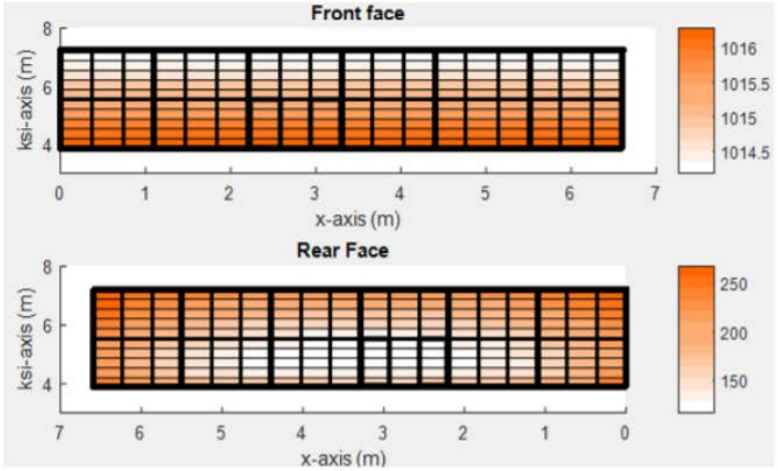


Fig. 9. Relative difference in I_L from the average for the one-high configuration on a sunny day, Mar. 6, 2018. (a) 8 A.M. (b) 10 A.M. (c) 12 P.M. (d) 2 P.M. (e) 4 P.M.

Border conditions are well represented.



12 modules: landscape configuration, 3 bypass diodes per modules, 5 mesh elements per bypass block

ines

A. Lindsay, "Modelling of Single-Axis Tracking Gain for Bifacial PV Systems," in Proc. 32nd European Photovoltaic Solar Energy Conference, Munich, Germany, 2016, pp. 1610–1617

Keith R. McIntosh, Malcolm D. Abbott, Benjamin A. Sudbury, Jenya Meydbray, "Mismatch Loss in Bifacial Modules Due to Nonuniform Illumination in 1-D Tracking Systems", *Photovoltaics IEEE Journal of*, vol. 9, no. 6, pp. 1504-1512, 2019.

T. Capelle, et al "A comparison of bifacial PV system modelling tools", 6th bifiPV Workshop, Amsterdam NL 2019

Looking at some details

- Validation
- Size of Array
- Edge Effects
- Racking/tracking torque tubes

Impact of Edges Effects + torquetube shading losses

Raytracing can account for torquetube and edge brightening.

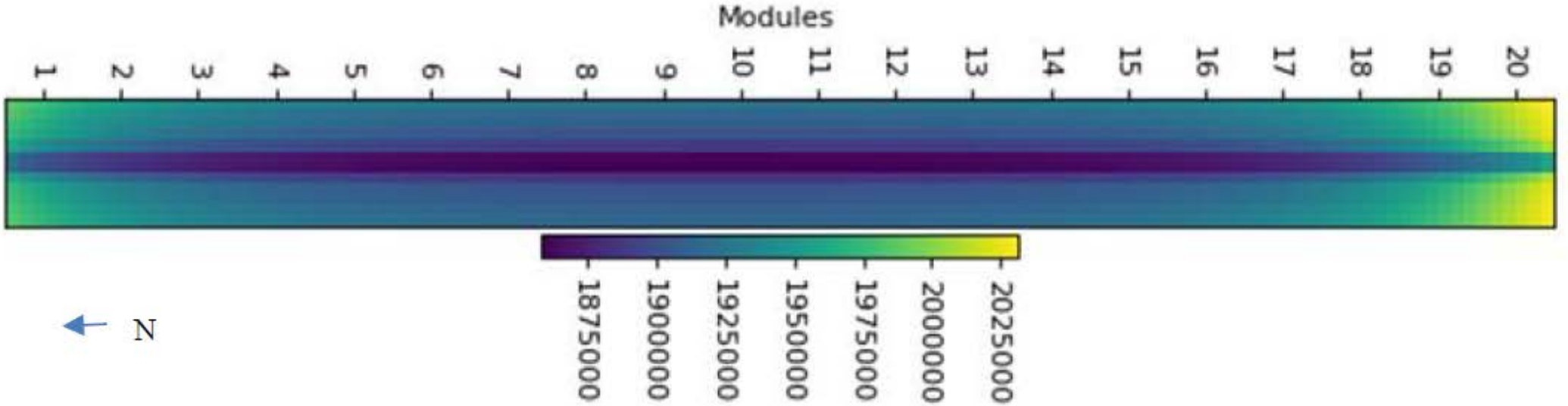


Figure 5 Year cumulative G_{total} [Whm^{-2}] for an interior row of 20 module × 7 rows HSAT at 1.5-m hub height, considering torque tube.

Deline, C., Ayala Pelaez, S., MacAlpine, S., Olalla, C. «Estimating and Parameterizing Mismatch Power Loss in Bifacial Photovoltaic Systems», (submitted PinPV)

(Tutorial 9)

Shading Factors

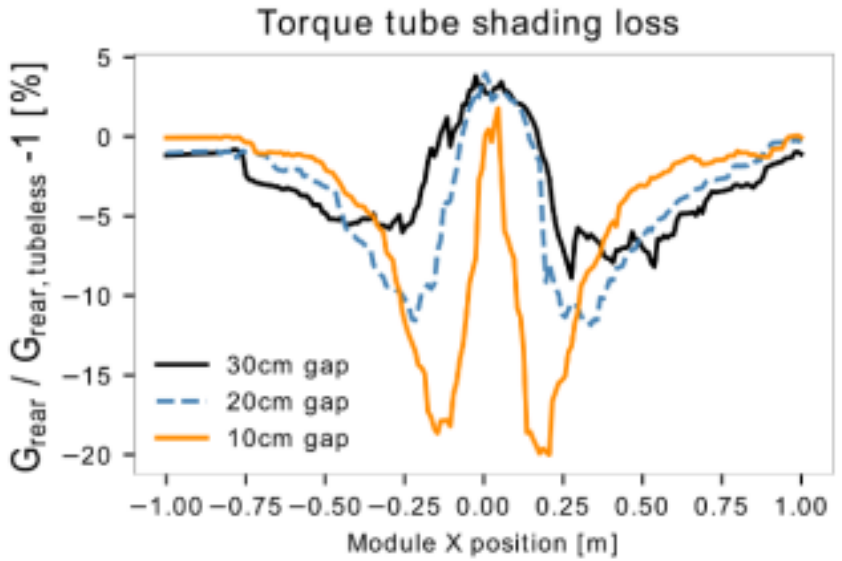


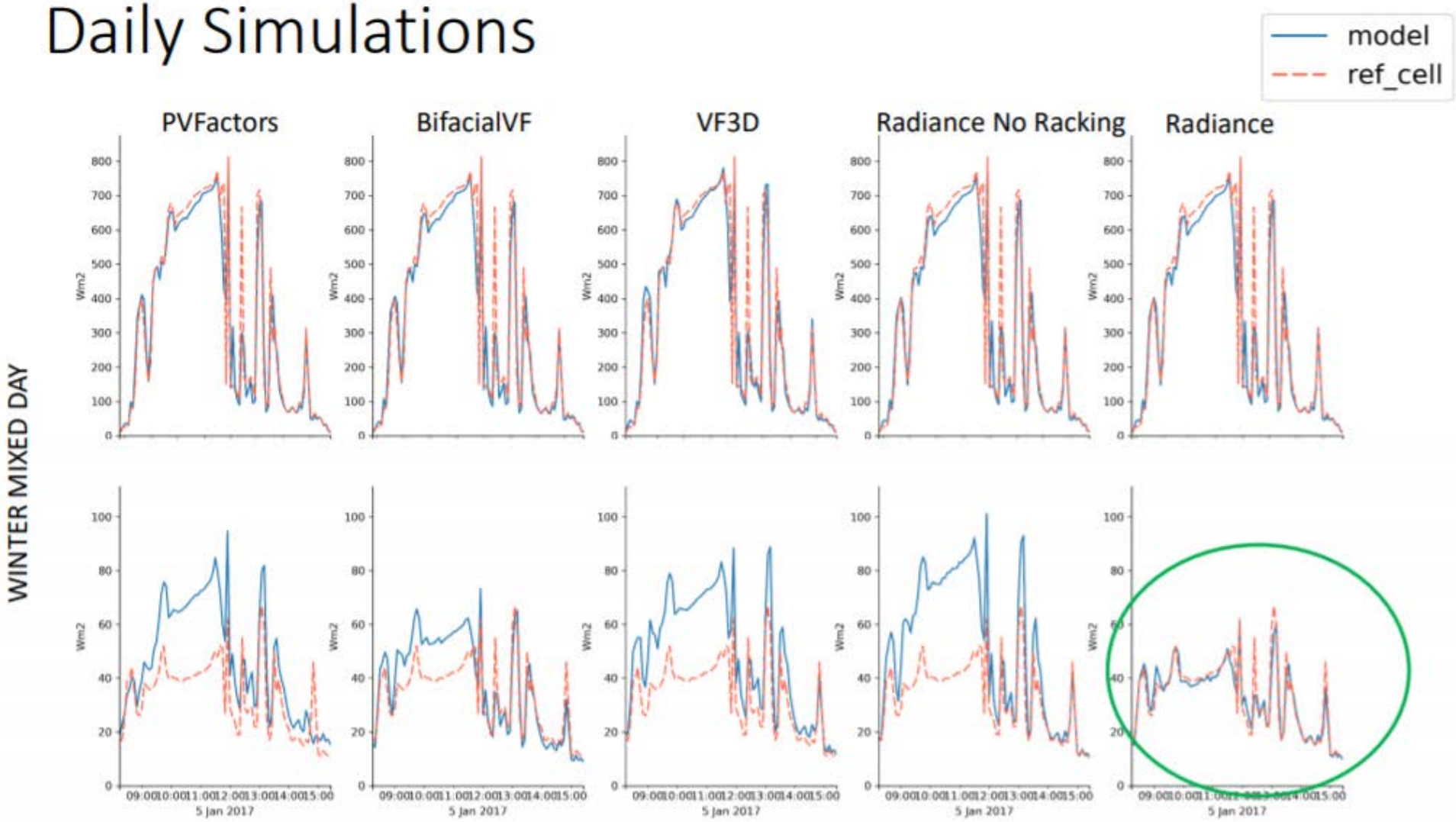
Fig. 13. a) RADIANCE image showing torque tube behind a modules row and b) G_{rear} across the module averaged over a sunny day.

S. Ayala Pelaez, C. Deline, S. M. MacAlpine, B. Marion, J. S. Stein and R. K. Kostuk, "Comparison of Bifacial Solar Irradiance Model Predictions With Field Validation," in *IEEE Journal of Photovoltaics*, vol. 9, no. 1, pp. 82-88, Jan. 2019. doi: 10.1109/JPHOTOV.2018.2877000

*Correction to this figure: Silvana Ayala Pelaez, Chris Deline, Peter Greenberg, Joshua S. Stein, Raymond K. Kostuk, "Corrections to “model and validation of single-axis tracking with bifacial pv” [may 19 715-721]", *Photovoltaics IEEE Journal of*, vol. 9, no. 6, pp. 1880-1880, 2019.

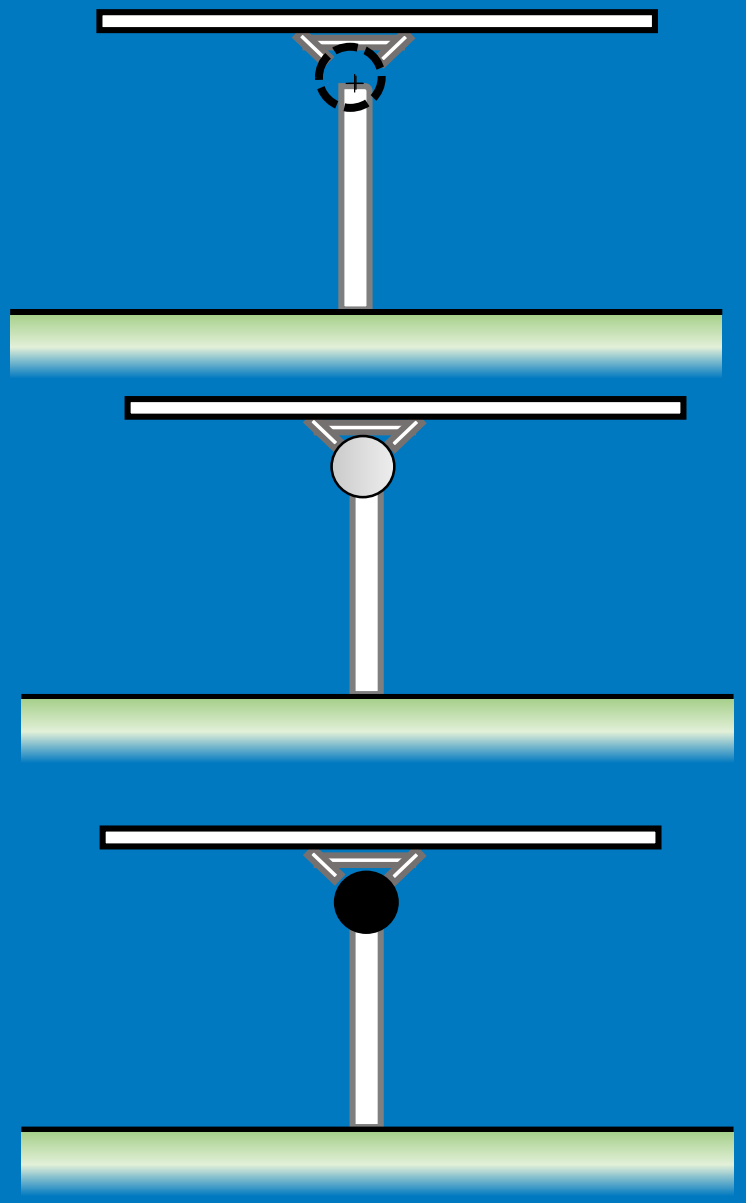
https://www.nrel.gov/docs/fy19osti/72039.pdf

Daily Simulations



T. Capelle, et al "A comparison of bifacial PV system modelling tools", 6th bifiPV Workshop, Amsterdam, NL 2019

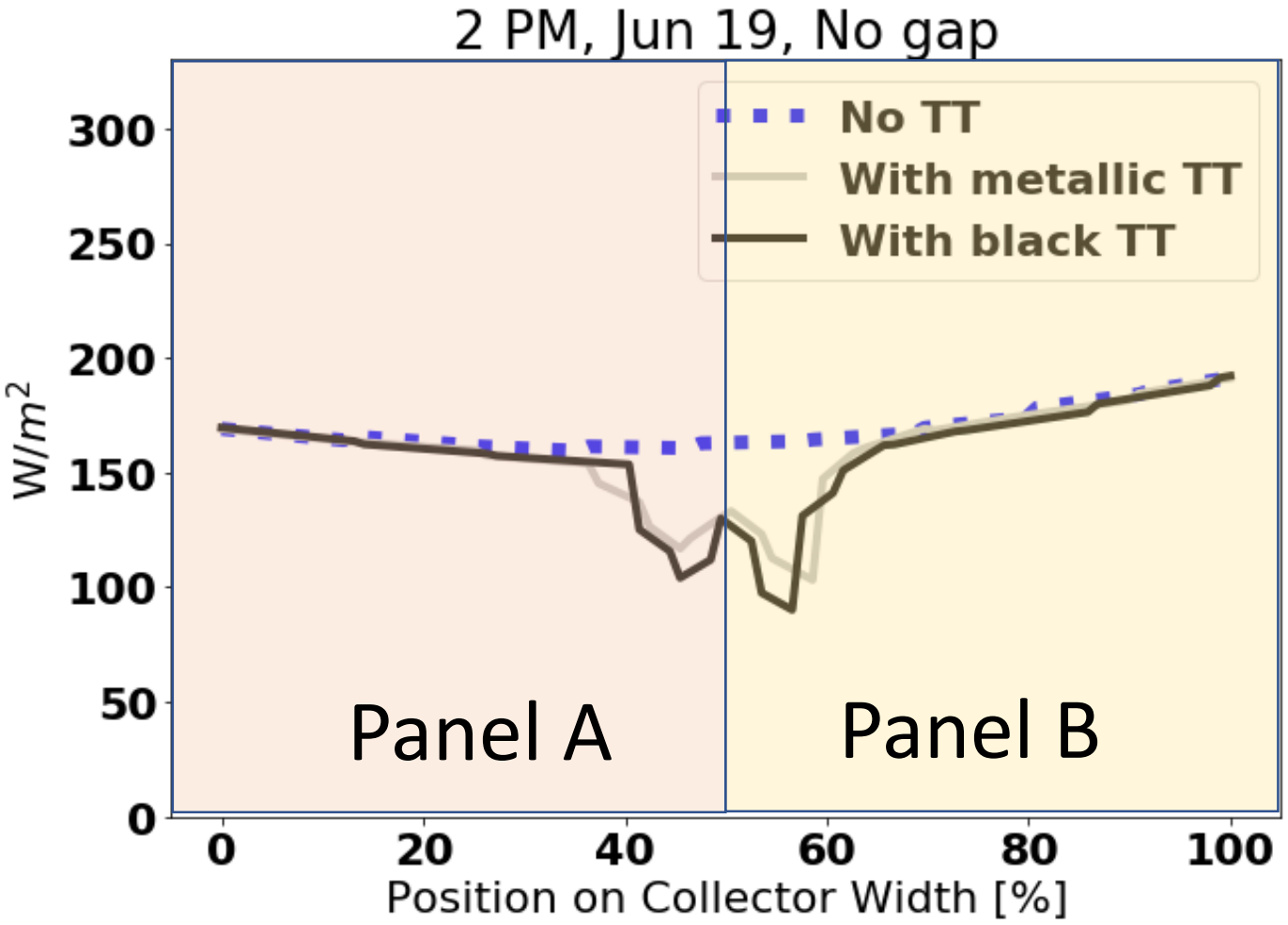
Varying torquetube reflectivity



$$G_{rear}\ \text{Shading Factor} = 1 - \frac{\sum_{t=0}^{8760} G_{rear\ average}\ (\text{with } tube)}{\sum_{t=0}^{8760} G_{rear\ average}\ (\text{no } tube)}$$

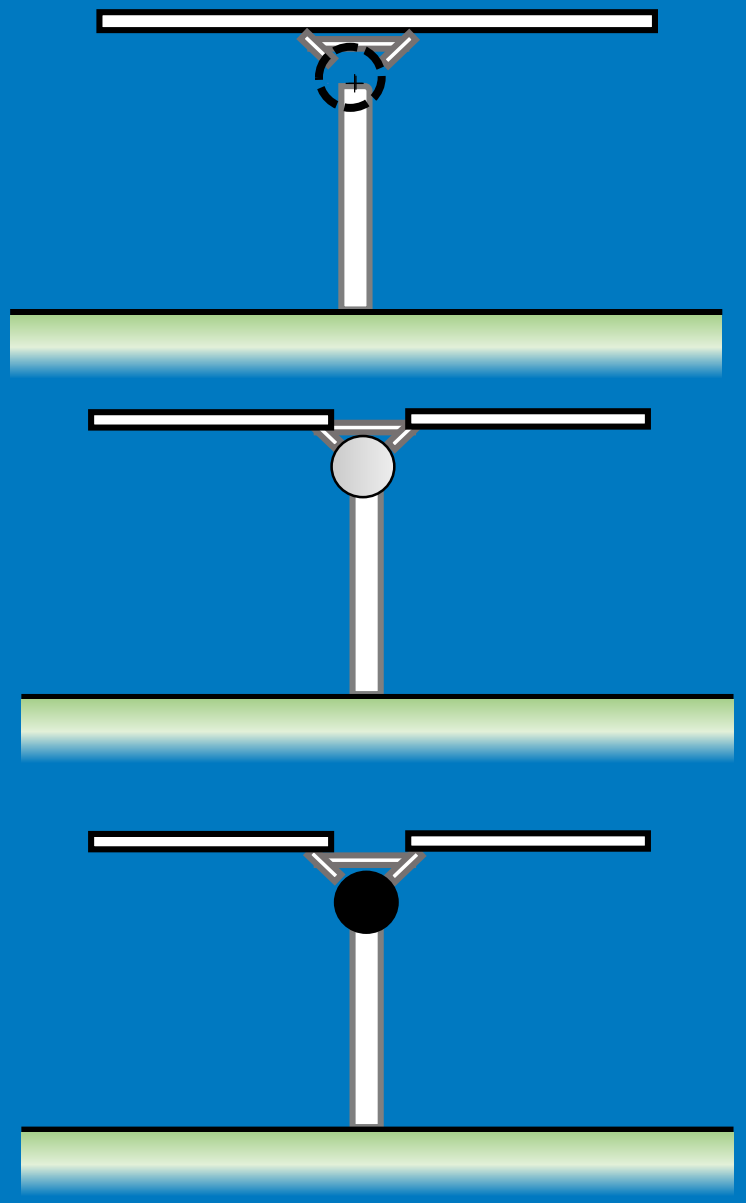
5.7% Shading Factor

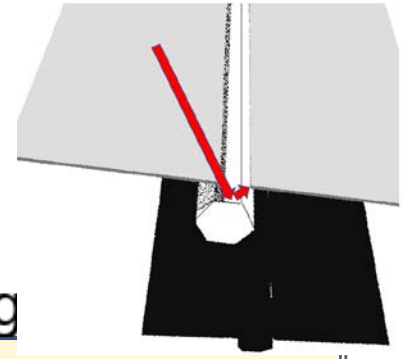
7.8% Shading Factor



Ayala Pelaez, C. Deline, et al "Effect of torque-tube parameters on rear-irradiance and rear-shading loss for bifacial PV performance on 1-axis tracking systems". 46th PVSC Proceedings, Chicago 2019.
ttps://www.nrel.gov/docs/fy20osti/73203.pdf Slides: https://www.nrel.gov/docs/fy19osti/74236.pdf

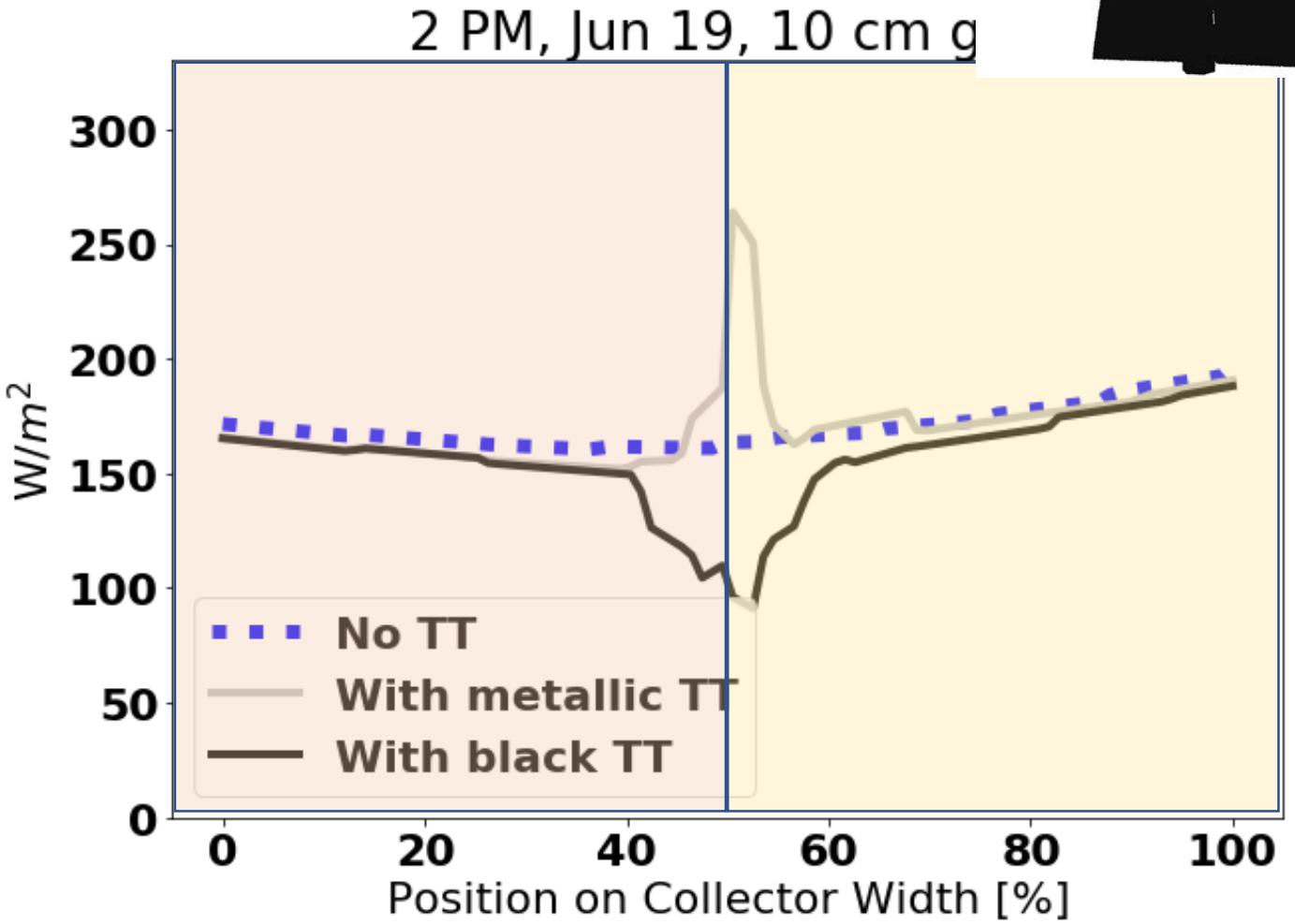
Varying torquetube reflectivity





-1.7% Shading Factor

8.5% Shading Factor



Ayala Pelaez, C. Deline, et al "Effect of torque-tube parameters on rear-irradiance and rear-shading loss for bifacial PV performance on 1-axis tracking systems". 46th PVSC Proceedings, Chicago 2019.
ttps://www.nrel.gov/docs/fy20osti/73203.pdf Slides: https://www.nrel.gov/docs/fy19osti/74236.pdf

On electrical mismatch…

- bifacial_radiance provides irradiance results at the module.
- Coupled to SUNPOWER PVMismatch for simple electrical modeling.
- Working on further streamlining and result interpretation, as well as reduced-order models.

In the meantime, we have tutorials

Deline, C., Ayala Pelaez, S., MacAlpine, S., Olalla, C. «Estimating and Parameterizing Mismatch Power Loss in Bifacial Photovoltaic Systems», (submitted PinPV)
36th EUPVSEC version: https://www.nrel.gov/docs/fy20osti/73541.pdf
Slides: https://www.nrel.gov/docs/fy19osti/74885.pdf
Poster: https://www.nrel.gov/docs/fy19osti/74831.pdf

High Performance Computing Integration

Yearly hourly simulations take
4 days on a PC,
HPC RUNS in 1 Minute!

Conclusions

- Energy gain on bifacial systems depends on the site configuration and surface albedo. Models like SAM, PVSyst, and bifacial_radiance can assist with system design and power estimation.
- Model validation is underway, and current VF software (SAM, PVSyst) appears to be conservative relative to measured rear irradiance.
- Raytrace softwares, such as the open source bifacial_raytrace, allow for more detailed simulations, which provide better agreement with results. It can help calculate particularities of your system (i.e. shading factor and electrical mismatch), and also to develop reduced-order models.
- Computationally intensive? Try HPC... or AWS (in theaters near you in 2020)

Thank you

www.nrel.gov

silvana.ayala@nrel.gov
chris.deline@nrel.gov

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