

# The Subtle Art of Bifacial Performance Modeling

Silvana Ayala Peláez, Chris Deline, Bill Marion,  
Matthew Muller, Joshua S. Stein, Cameron Stark

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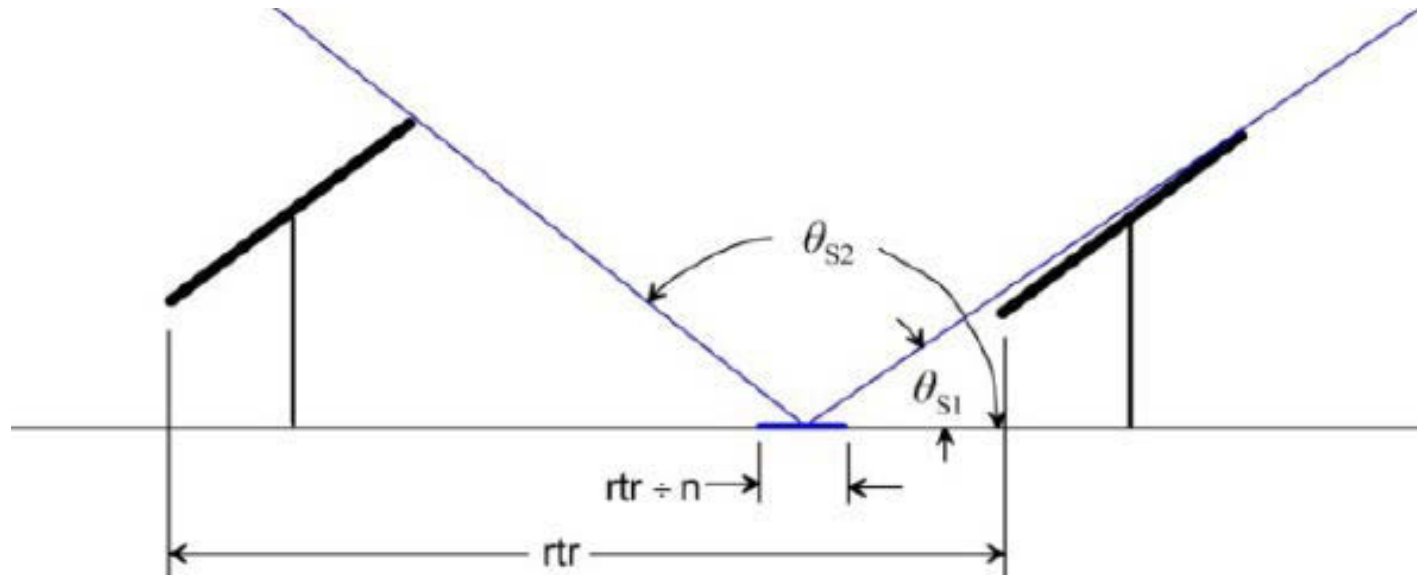


## Bifacial performance modeling

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.

# View Factor Model for Rear Irradiance



Simple

basic  
geometry

Fast

computationally  
inexpensive

Common

**Behind**  
SAM, Pvsyst, and others

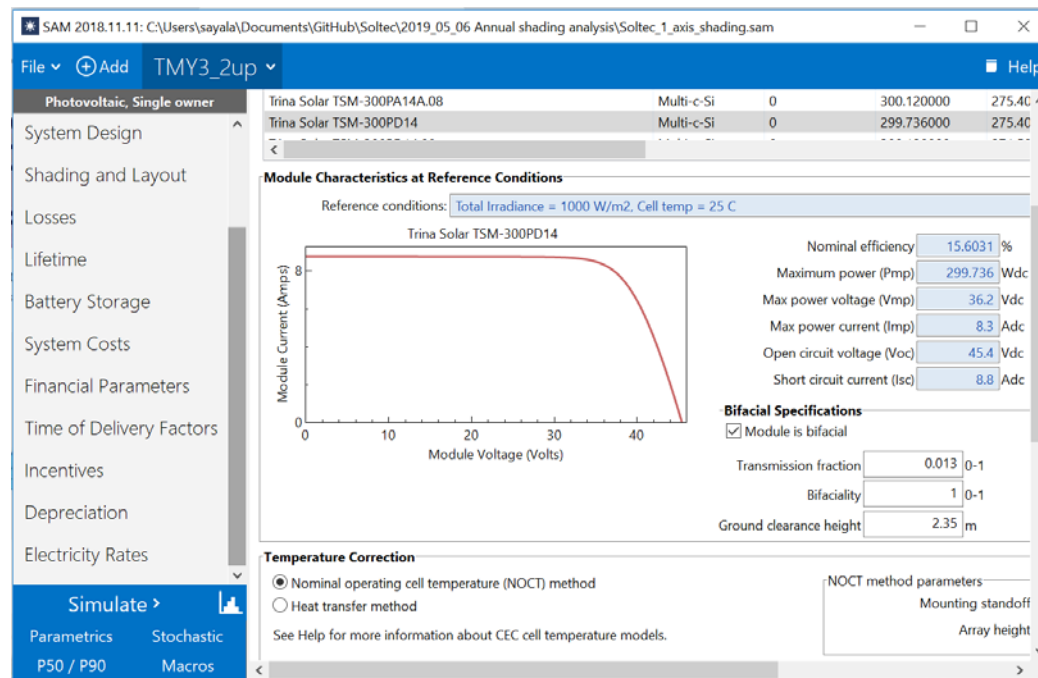
Simple

basic  
geometry

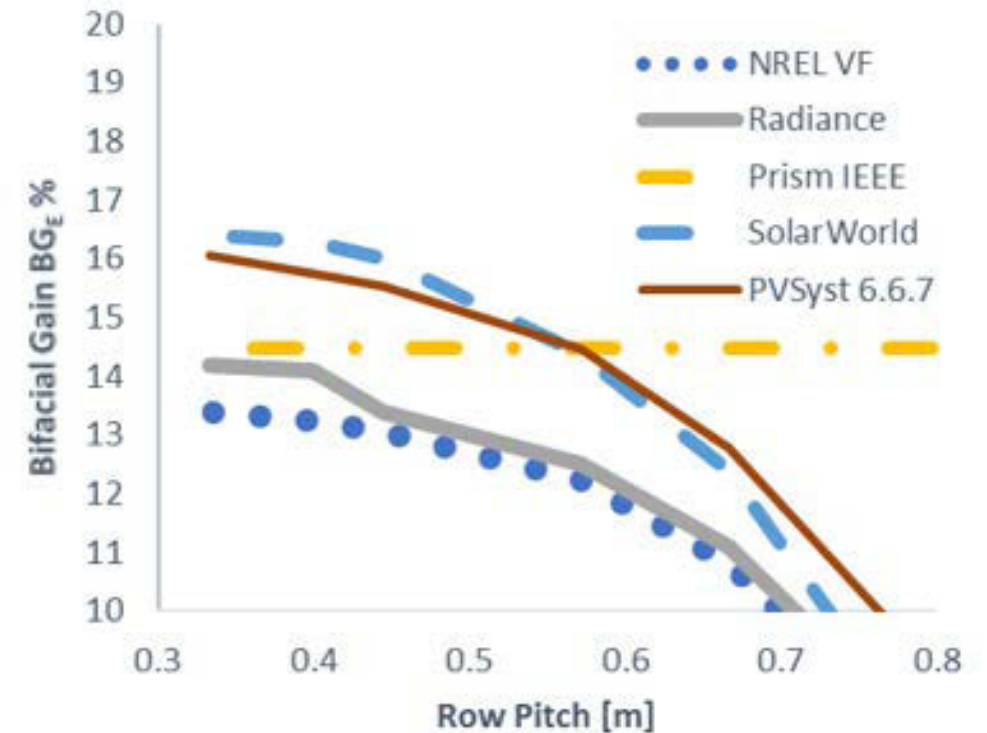


# NREL Models

- [OPENSource](#)
- [Bifacial vf: https://github.com/NREL/bifacialvf](https://github.com/NREL/bifacialvf)
- Implemented in SAM:



## Published Comparison of Models With Validation data:



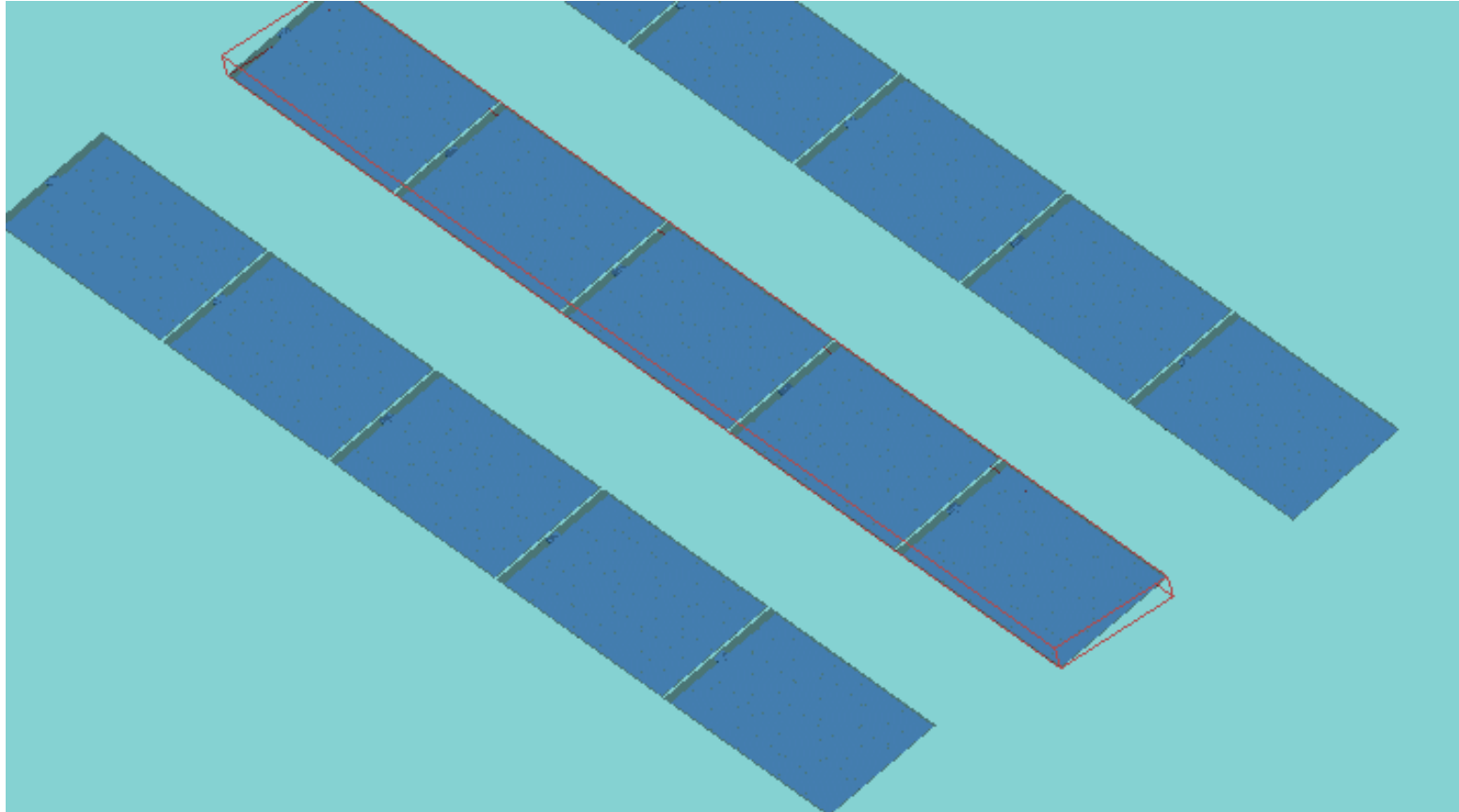
S. Ayala Pelaez, C. Deline, S. MacAlpine, B. Marion, J. Stein, R. Kostuk, "Comparison of bifacial solar irradiance model predictions with field validation" IEEE Journal of Photovoltaics, 2019, vol 9 no. 1, pp. 82-88.

N. DiOrto, C. Deline, "Bifacial simulation in SAM", presented at 5<sup>th</sup> BifiPV in Denver, CO 2018.



# Rear Irradiance Modeling through **bifacial\_radiance**

# Bifacial\_Radiance Model for Rear Irradiance

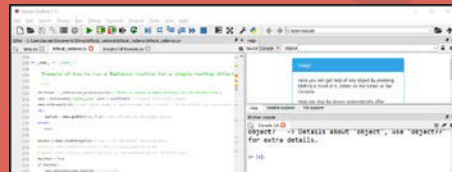


**Complicated geometries possible, including racking and terrain.**

**Radiance uses **backward ray-trace** to evaluate the irradiance ( $\text{W}/\text{m}^2$ ) at the modules**

# Bifacial\_Radiance Model for Rear Irradiance

Open Source!



```
Command Prompt
Microsoft Windows [Version 10.0.17134.523]
(c) 2018 Microsoft Corporation. All rights reserved.

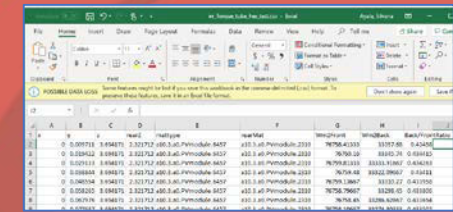
U:\>C:
C:\>
```

```
gambos\my_custom_panel.rad
gambos\my_custom_panel.rad
gambos\my_custom_panel.rad
gambos\my_custom_panel.rad
gambos\my_custom_panel.rad
gambos\my_custom_panel.rad
gambos\my_custom_panel.rad
gambos\my_custom_panel.rad
gambos\my_custom_panel.rad
gambos\my_custom_panel.rad
```

```
my_custom_panel.rad - Notepad
File Edit Format View Help
gambos black PVmodule 1.996 0.931 0.82 | sform -t -0.908 0 0 -a 2 -t 0 0.931 0
gambos Metal_Grey hortuola3 1.996 0.875 0.12990310548 | sform -t -0.908 0.935 -0.30410310548
gambos Metal_Grey hortuola3 1.996 0.875 0.12990310548 | sform -t -0.908 0.935 -0.0649519052318 -rx 60 -t 0 0.9
gambos Metal_Grey hortuola3 1.996 0.875 0.12990310548 | sform -t -0.908 -0.935 -0.0649519052318 -rx -60 -t 0 0
```

```
my_custom_panel_233_1209_20x7rad - Notepad
File Edit Format View Help
|xform -rx 10 -t 0 0 2.35 -a 20 -t 2.806 0 0 -a 7 -t 0 12.097 0 -1 1
|t -19.96 -36.291 0 -rz 0 objects/my_custom_panel.rad
```

```
gambos\my_custom_panel.rad
gambos\my_custom_panel.rad
gambos\my_custom_panel.rad
gambos\my_custom_panel.rad
gambos\my_custom_panel.rad
gambos\my_custom_panel.rad
gambos\my_custom_panel.rad
gambos\my_custom_panel.rad
gambos\my_custom_panel.rad
gambos\my_custom_panel.rad
```



	A	B	C	D	E	F	G	H	I	J
1										
2	0	0.00718	0.00817	1.02372	480.0	0.0	0.0	0.0	0.0	0.0
3	0	0.00842	0.00817	1.02372	480.0	0.0	0.0	0.0	0.0	0.0
4	0	0.01113	0.00817	1.02372	480.0	0.0	0.0	0.0	0.0	0.0
5	0	0.00848	0.00817	1.02372	480.0	0.0	0.0	0.0	0.0	0.0
6	0	0.00718	0.00817	1.02372	480.0	0.0	0.0	0.0	0.0	0.0
7	0	0.00842	0.00817	1.02372	480.0	0.0	0.0	0.0	0.0	0.0
8	0	0.00718	0.00817	1.02372	480.0	0.0	0.0	0.0	0.0	0.0
9	0	0.00842	0.00817	1.02372	480.0	0.0	0.0	0.0	0.0	0.0

Bifacial\_radiance is a python wrapper for calling and using Radiance, with specific functions to generate geometry (text files) related to bifacial pv systems



# New GUI! v3

tk

### Main Control

Input Variables File:    
   
TestFolder:    
WeatherFile Input:  GetEPW  ReadEPW / TMY  
Get EPW (Lat/Lon):    
EPW / TMY File:    
Simulation Name:

### Simulation Control

Fixed, Cumulative Sky Yearly
Fixed, Cumulative Sky with Start/End times
Fixed, Hourly by Timestamps
Fixed, Hourly for the Whole Year
Tracking, Cumulative Sky Yearly
Tracking, Hourly for a Day
Tracking, Hourly with Start/End times
Tracking, Hourly for the Whole Year

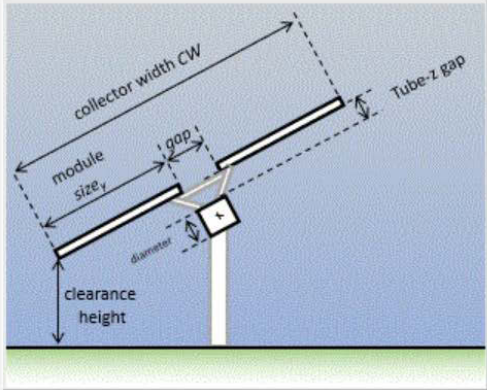
StartDate ( MM | DD | HH ):     
Enddate ( MM | DD | HH ):     
Timestamp Start:   
Timestamp End:

### Tracking Parameters

Backtrack:  True  False  
Limit Angle (deg):   
Angle delta (deg):   
Axis of Rotation:  Torque Tube  Panels

### TorqueTube Parameters

TorqueTube:    
Diameter:   
Tube type:  Round  Square  Hex  Oct  
TorqueTube Material:  Metal\_Grey  Black



### Module Parameters

Prism Solar Bi60

Number of Panels:   
Cell Level Module:    
numcells x:  numcells y:   
Size Xcell:  Size Ycell:   
Xcell gap:  Ycell gap:   
Module size x:  y:   
Xgap | Ygap | Zgap:     
Bifacial Factor (i.e. 0.9):    
Module Name:   
Rewrite Module:  True  False

### Scene Parameters

Row spacing by:  GCR  Pitch  
GCR:  Pitch:   
Albedo:   
# Mods:  # Rows:   
Azimuth Angle (i.e. 180 for South):   
Clearance height:  Tilt:   
Axis Azimuth (i.e. 180 for EW HSATtrackers):   
Hub height:

### Analysis Parameters

# Sensors:   
Mod Wanted:  Row Wanted:

[https://github.com/NREL/bifacial\\_radiance](https://github.com/NREL/bifacial_radiance)



# New GUI: features

tk

### Main Control

Input Variables File:

TestFolder:

WeatherFile Input:  GetEPW  ReadEPW / TMY

Get EPW (Lat/Lon):

EPW / TMY File:

Simulation Name:

### Simulation Control

Fixed, Cumulative Sky Yearly

Fixed, Cumulative Sky with Start/End times

Fixed, Hourly by Timestamps

Fixed, Hourly for the Whole Year

Tracking, Cumulative Sky Yearly

Tracking, Hourly for a Day

Tracking, Hourly with Start/End times

Tracking, Hourly for the Whole Year

StartDate (MM | DD | HH):

EndDate (MM | DD | HH):

Timestamp Start:

Timestamp End:

### Tracking Parameters

Backtrack:  True  False

Limit Angle (deg):

Angle delta (deg):

Axis of Rotation:  Torque Tube  Panels

### TorqueTube Parameters

TorqueTube:

Diameter:

Tube type:  Round  Square  Hex  Oct

TorqueTube Material:  Metal\_Grey  Black

### Module Parameters

Prism Solar Bi60

Number of Panels:

Cell Level Module:  False  True

numcells x:	<input type="text" value="12"/>	numcells y:	<input type="text" value="6"/>
Size Xcell:	<input type="text" value="0.15"/>	Size Ycell:	<input type="text" value="0.15"/>
Xcell gap:	<input type="text" value="0.01"/>	Ycell gap:	<input type="text" value="0.01"/>
Module size x:	<input type="text" value="0.98"/>	y:	<input type="text" value="1.98"/>
Xgap   Ygap   Zgap:	<input type="text" value="0.05"/>	<input type="text" value="0.15"/>	<input type="text" value="0.10"/>

Bifacial Factor (i.e. 0.9):

Module Name:

Rewrite Module:  True  False

### Scene Parameters

Row spacing by:  GCR  Pitch

GCR:  Pitch:

Albedo:

# Mods:  # Rows:

Azimuth Angle (i.e. 180 for South):

Clearance height:  Tilt:

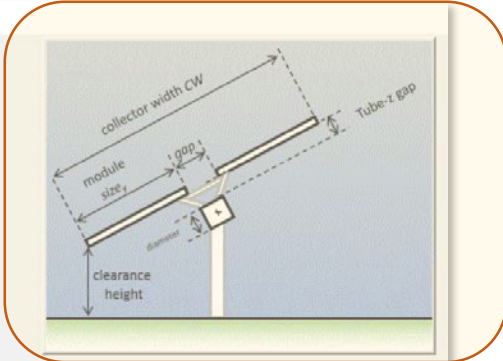
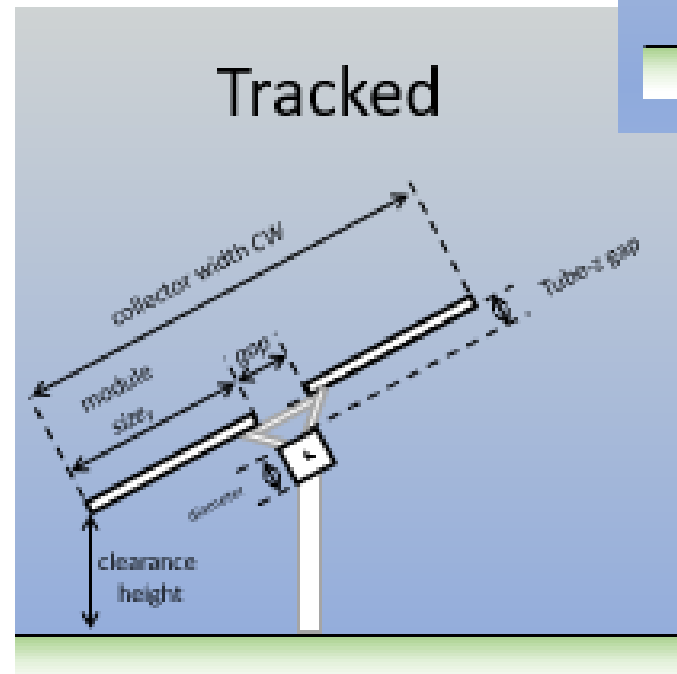
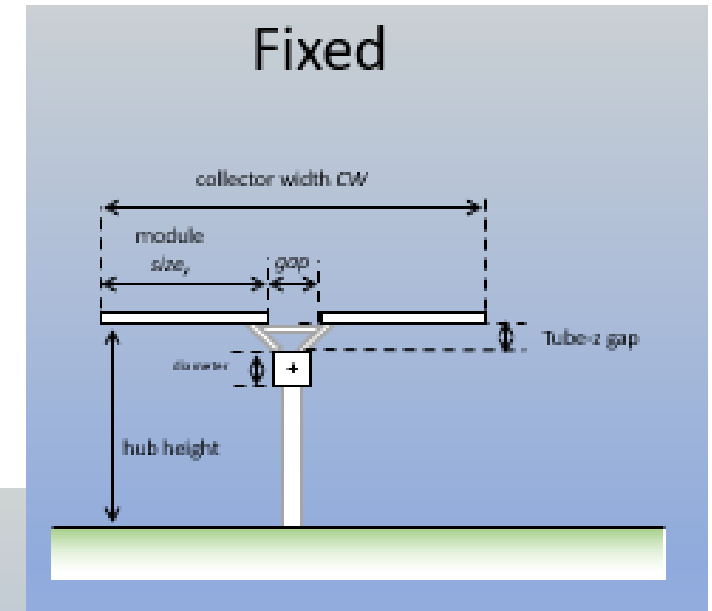
Axis Azimuth (i.e. 180 for EW HSATrackers):

Hub height:

### Analysis Parameters

# Sensors:

Mod Wanted:  Row Wanted:

# New GUI: features

**Main Control**

Input Variables File: **BB** [Search] [READ] [SAVE]

TestFolder: **C:\Users\sayala\Docum** [Search]

WeatherFile Input:  GetEPW  ReadEPW / TMY

Get EPW (Lat/Lon): **33** **-110**

EPW / TMY File: **EPWs\USA\_VA\_Richm** [Search]

Simulation Name: **Demo1**

**Simulation Control**

Fixed, Cumulative Sky Yearly
Fixed, Cumulative Sky with Start/End times
Fixed, Hourly by Timestamps
Fixed, Hourly for the Whole Year
Tracking, Cumulative Sky Yearly
Tracking, Hourly for a Day
Tracking, Hourly with Start/End times
Tracking, Hourly for the Whole Year

StartDate (MM | DD | HH): **6** **21** **5**

Enddate (MM | DD | HH): **6** **30** **20**

Timestamp Start: **4020**

Timestamp End: **4024**

**Tracking Parameters**

Backtrack:  True  False

Limit Angle (deg): **60**

Angle delta (deg): **5**

Axis of Rotation:  Torque Tube  Panels

**TorqueTube Parameters**

TorqueTube:  True  False

Diameter: **0.1**

Tube type:  Round  Square  Hex  Oct

TorqueTube Material:  Metal\_Grey  Black

**Diagram**

**Module Parameters** Prism Solar Bi60

Number of Panels:	2		
Cell Level Module:	<input type="checkbox"/> False	<input checked="" type="checkbox"/> True	
numcells x:	12	numcells y:	6
Size Xcell:	0.15	Size Ycell:	0.15
Xcell gap:	0.01	Ycell gap:	0.01
Module size x:	0.98	y:	1.98
Xgap   Ygap   Zgap:	0.05	0.15	0.10
Bifacial Factor (i.e. 0.9):	0.9	[VIEW]	
Module Name:	Prism Solar Bi60		
Rewrite Module:	<input checked="" type="checkbox"/> True	<input type="checkbox"/> False	

**Scene Parameters**

Row spacing by:  GCR  Pitch

GCR: **0.35** Pitch: **10**

Albedo: **0.62**

# Mods: **20** # Rows: **7**

Azimuth Angle (i.e. 180 for South): **180**

Clearance height: **0.8** Tilt: **10**

Axis Azimuth (i.e. 180 for EW HSATrackers): **180**

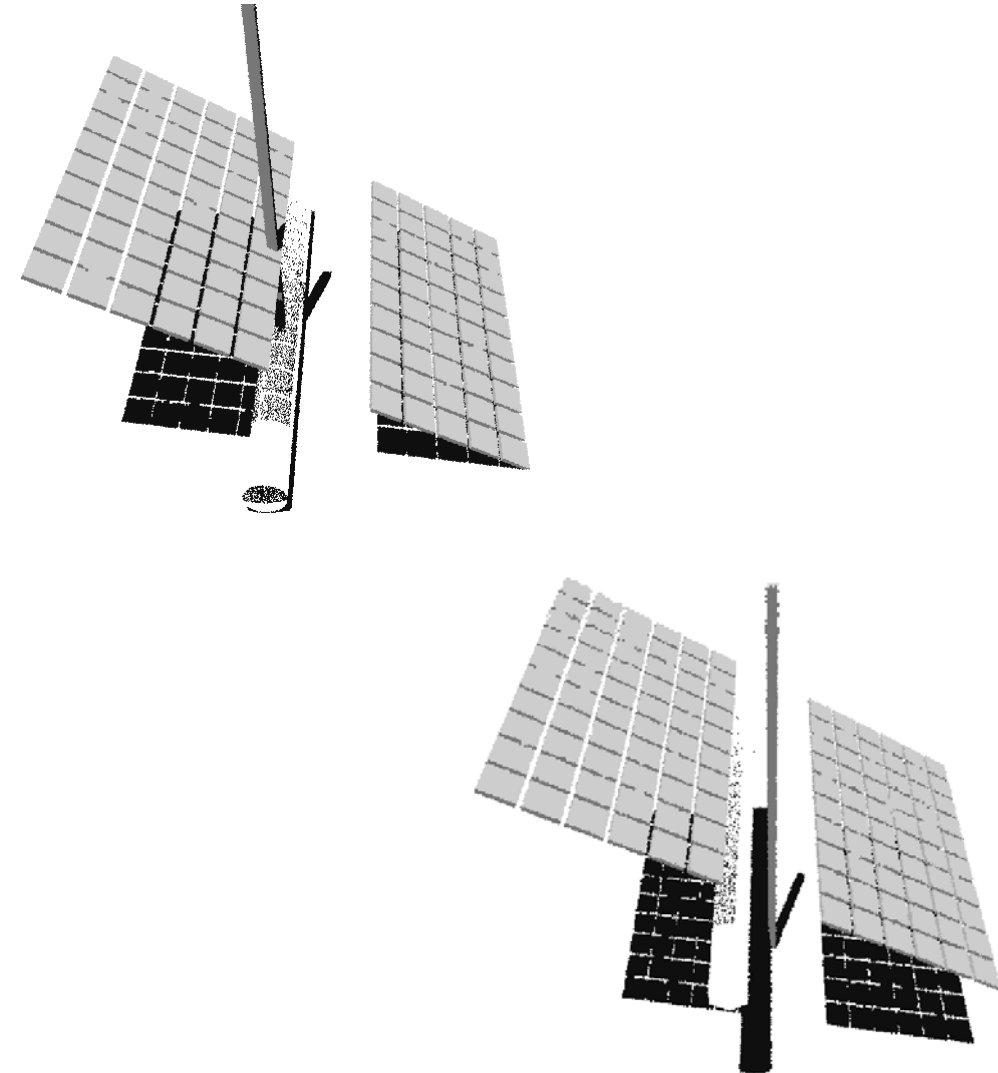
Hub height: **0.9** [VIEW]

**Analysis Parameters**

# Sensors: **9**

Mod Wanted: **10** Row Wanted: **3**

[CLEAR] [DEFAULT] [RUN]



# New GUI: features

**Main Control**

Input Variables File:

TestFolder:

WeatherFile Input:  GetEPW  ReadEPW / TMY

Get EPW (Lat/Lon):

EPW / TMY File:

Simulation Name:

**Simulation Control**

Fixed, Cumulative Sky Yearly
Fixed, Cumulative Sky with Start/End times
Fixed, Hourly by Timestamps
Fixed, Hourly for the Whole Year
Tracking, Cumulative Sky Yearly
Tracking, Hourly for a Day
Tracking, Hourly with Start/End times
Tracking, Hourly for the Whole Year

StartDate (MM | DD | HH):

Enddate (MM | DD | HH):

Timestamp Start:

Timestamp End:

**Tracking Parameters**

Backtrack:  True  False

Limit Angle (deg):

Angle delta (deg):

Axis of Rotation:  Torque Tube  Panels

**TorqueTube Parameters**

TorqueTube:

Diameter:

Tube type:  Round  Square  Hex  Oct

TorqueTube Material:  Metal\_Grey  Black

**Module Parameters** Prism Solar Bi60

Number of Panels:

Cell Level Module:  False  True

numcells x:	<input type="text" value="12"/>	numcells y:	<input type="text" value="6"/>
Size Xcell:	<input type="text" value="0.15"/>	Size Ycell:	<input type="text" value="0.15"/>
Xcell gap:	<input type="text" value="0.01"/>	Ycell gap:	<input type="text" value="0.01"/>
Module size x:	<input type="text" value="0.98"/>	y:	<input type="text" value="1.98"/>
Xgap   Ygap   Zgap:	<input type="text" value="0.05"/>	<input type="text" value="0.15"/>	<input type="text" value="0.10"/>

Bifacial Factor (i.e. 0.9):

Module Name:

Rewrite Module:  True  False

**Scene Parameters**

Row spacing by:  GCR  Pitch

GCR:  Pitch:

Albedo:

# Mods:  # Rows:

Azimuth Angle (i.e. 180 for South):

Clearance height:  Tilt:

Axis Azimuth (i.e. 180 for EW HSATrackers):

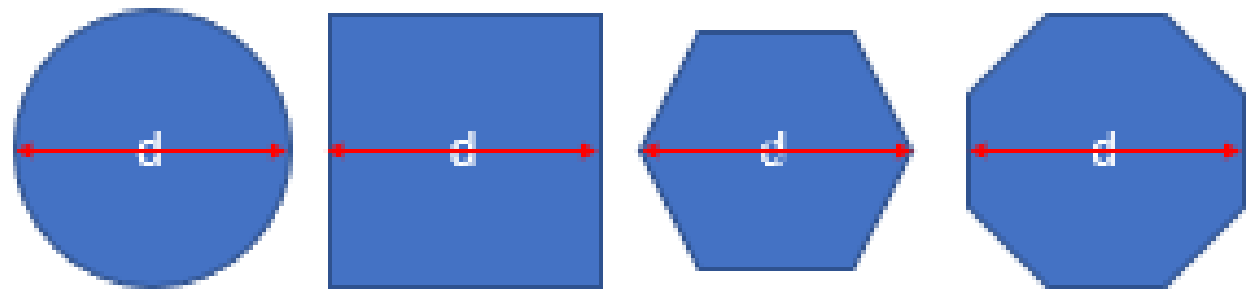
Hub height:

**Analysis Parameters**

# Sensors:

Mod Wanted:  Row Wanted:

**Diagram:** A 3D perspective diagram of a solar collector tube. Labels include: collector width CW, module size, gap, diameter, Tube-z gap, and clearance height.





# New GUI: features

**Main Control**

Input Variables File: **BB** Search

READ SAVE

TestFolder: C:\Users\sayala\Docum Search

WeatherFile Input:  GetEPW  ReadEPW / TMY

Get EPW (Lat/Lon): 33 -110

EPW / TMY File: EPWs\USA\_VA\_Richm Search

Simulation Name: Demo1

**Simulation Control**

Fixed, Cumulative Sky Yearly

Fixed, Cumulative Sky with Start/End times

Fixed, Hourly by Timestamps

Fixed, Hourly for the Whole Year

Tracking, Cumulative Sky Yearly

Tracking, Hourly for a Day

Tracking, Hourly with Start/End times

Tracking, Hourly for the Whole Year

StartDate (MM | DD | HH): 6 | 21 | 5

Enddate (MM | DD | HH): 6 | 30 | 20

Timestamp Start: 4020

Timestamp End: 4024

**Tracking Parameters**

Backtrack:  True  False

Limit Angle (deg): 60

Angle delta (deg): 5

Axis of Rotation:  Torque Tube  Panels

**TorqueTube Parameters**

TorqueTube:  True  False

Diameter: 0.1

Tube type:  Round  Square  Hex  Oct

TorqueTube Material:  Metal\_Grey  Black

**Module Parameters** Prism Solar Bi60

Number of Panels: 2

Cell Level Module:  False  True

numcells x: 12 numcells y: 6

Size Xcell: 0.15 Size Ycell: 0.15

Xcell gap: 0.01 Ycell gap: 0.01

Module size x: 0.98 y: 1.98

Xgap | Ygap | Zgap: 0.05 | 0.15 | 0.10

Bifacial Factor (i.e. 0.9): 0.9 VIEW

Module Name: Prism Solar Bi60

Rewrite Module:  True  False

**Scene Parameters**

Row spacing by:  GCR  Pitch

GCR: 0.35 Pitch: 10

Albedo: 0.62

# Mods: 20 # Rows: 7

Azimuth Angle (i.e. 180 for South): 180

Clearance height: 0.8 Tilt: 10

Axis Azimuth (i.e. 180 for EW HSATrackers): 180

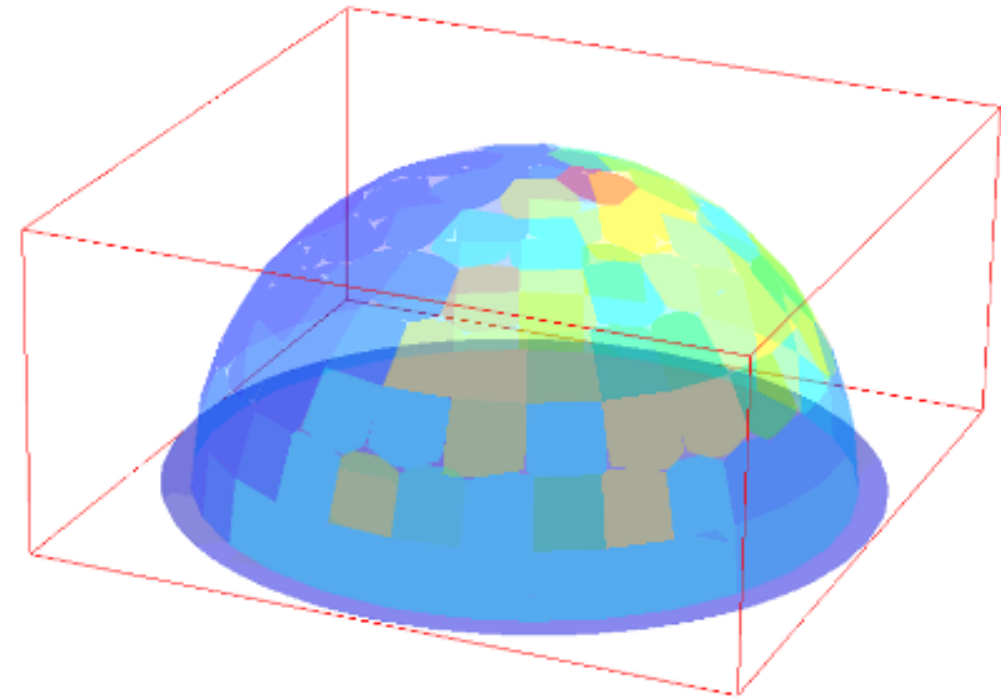
Hub height: 0.9 VIEW

**Analysis Parameters**

# Sensors: 9

Mod Wanted: 10 Row Wanted: 3

CLEAR DEFAULT RUN



Robinson, Stone "Irradiation modelling made simple: the cumulative sky approach" 2004

Hourly  
Cumulative  
Cumulative Tracking

S. Ayala Pelaez, C. Deline, P. Greenberg, J. S. Stein, and R. K. Kostuk, "Model and Validation of Single-Axis Tracking with Bifacial PV - Preprint," IEEE Journal of Photovoltaics, 2019, vol 9 no. 3, pp. 715-721.

# High Performance Computing **Integration**



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

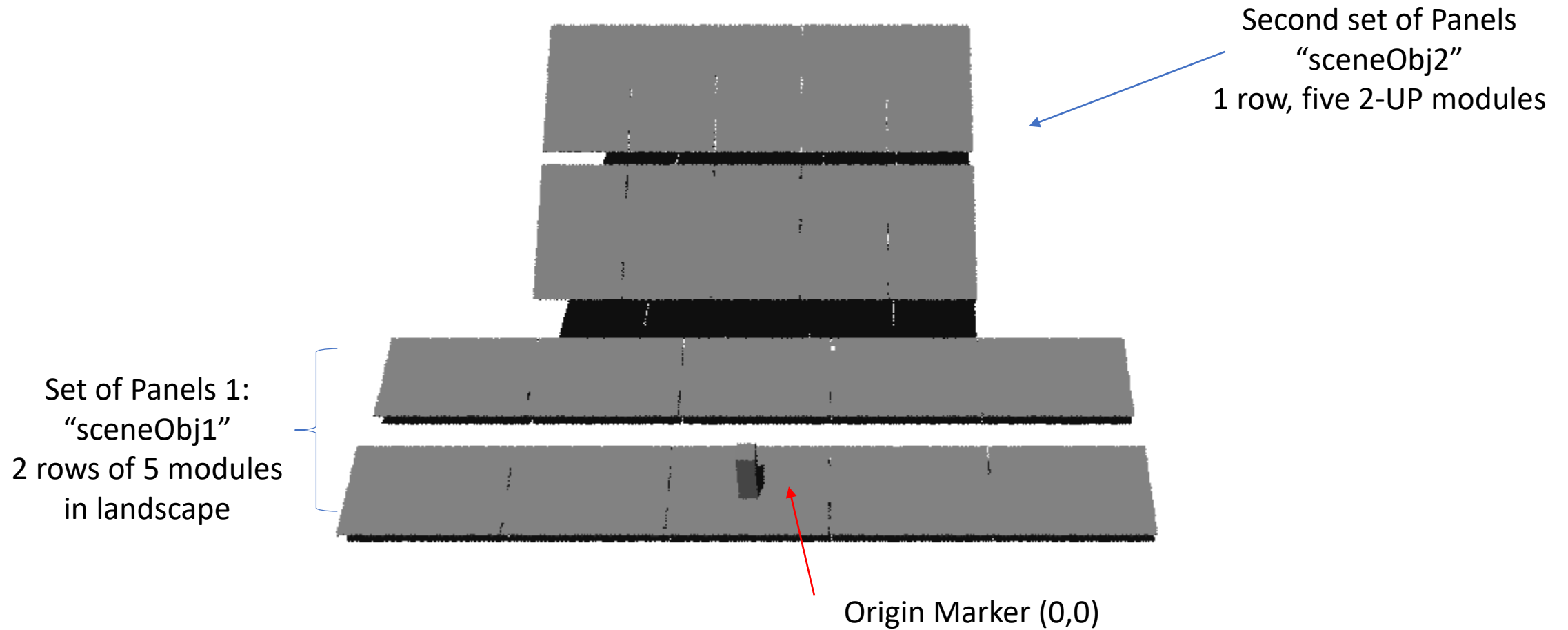


Non-GUI Features

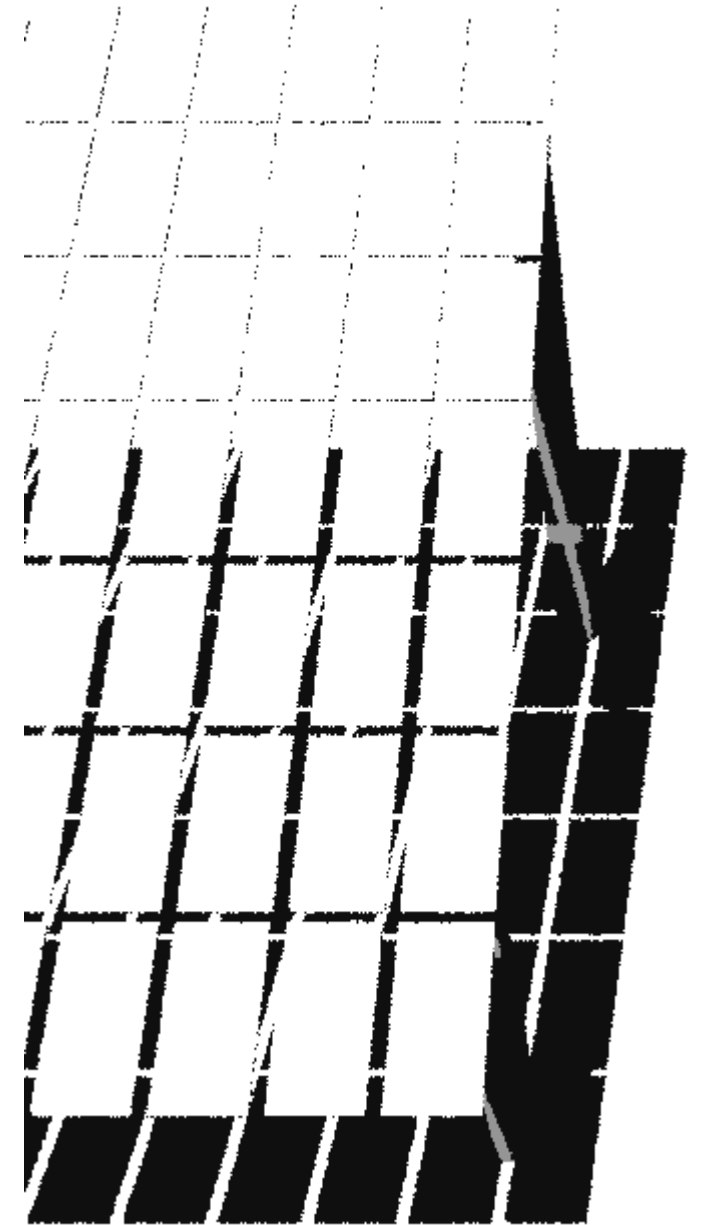
Bifacial\_radiance V3



# Multiple SceneObjects

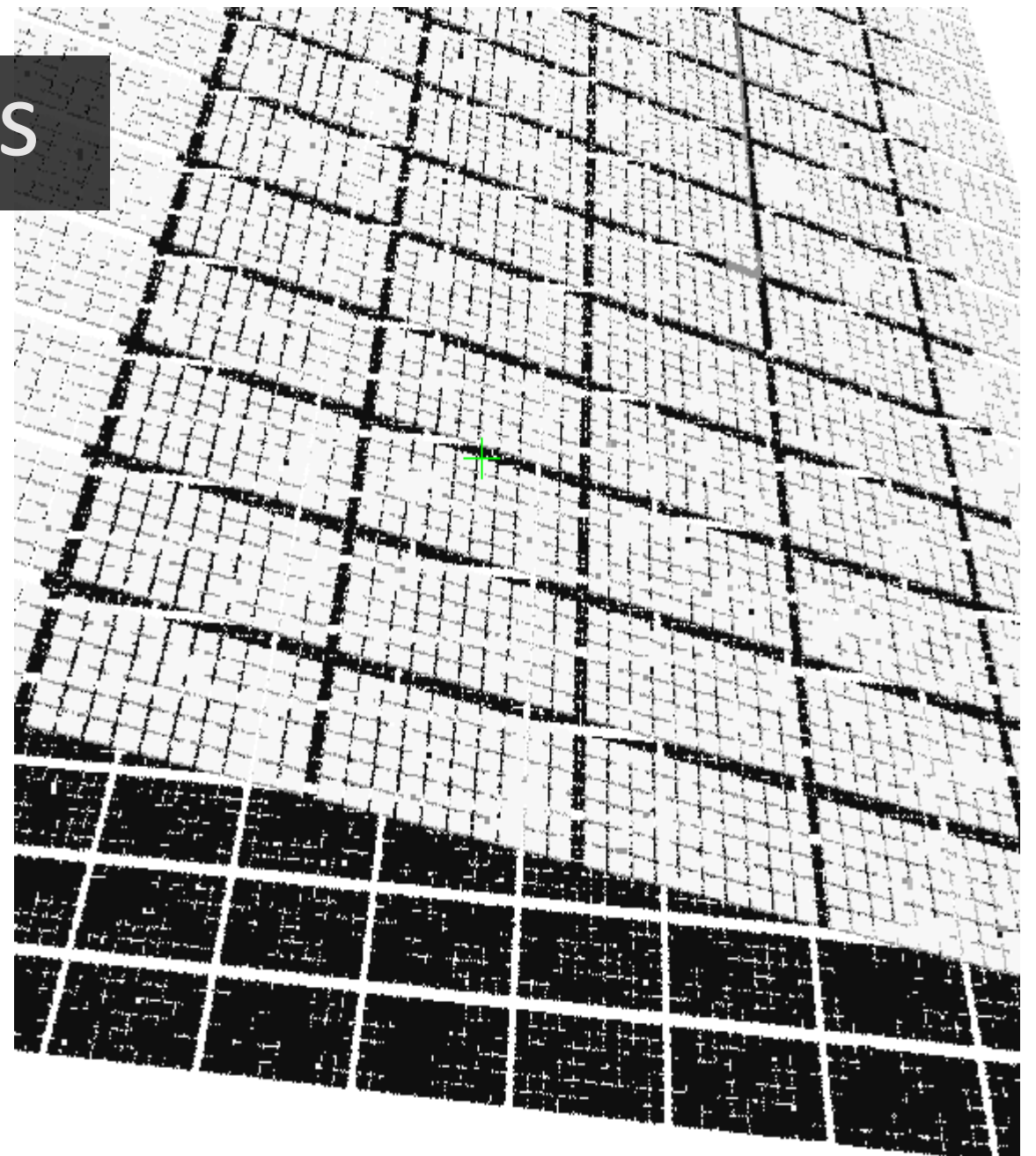
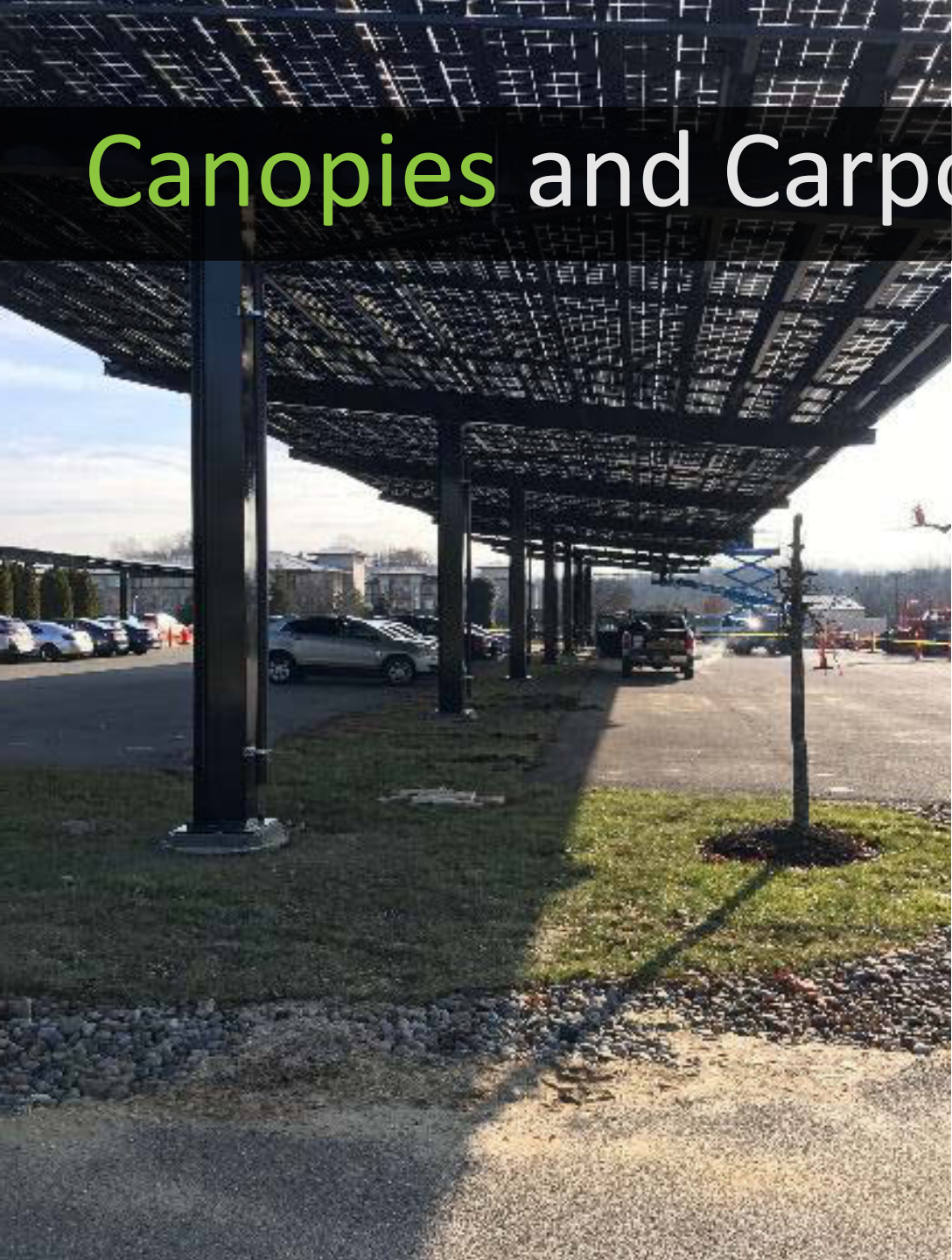


# Canopies and Carports



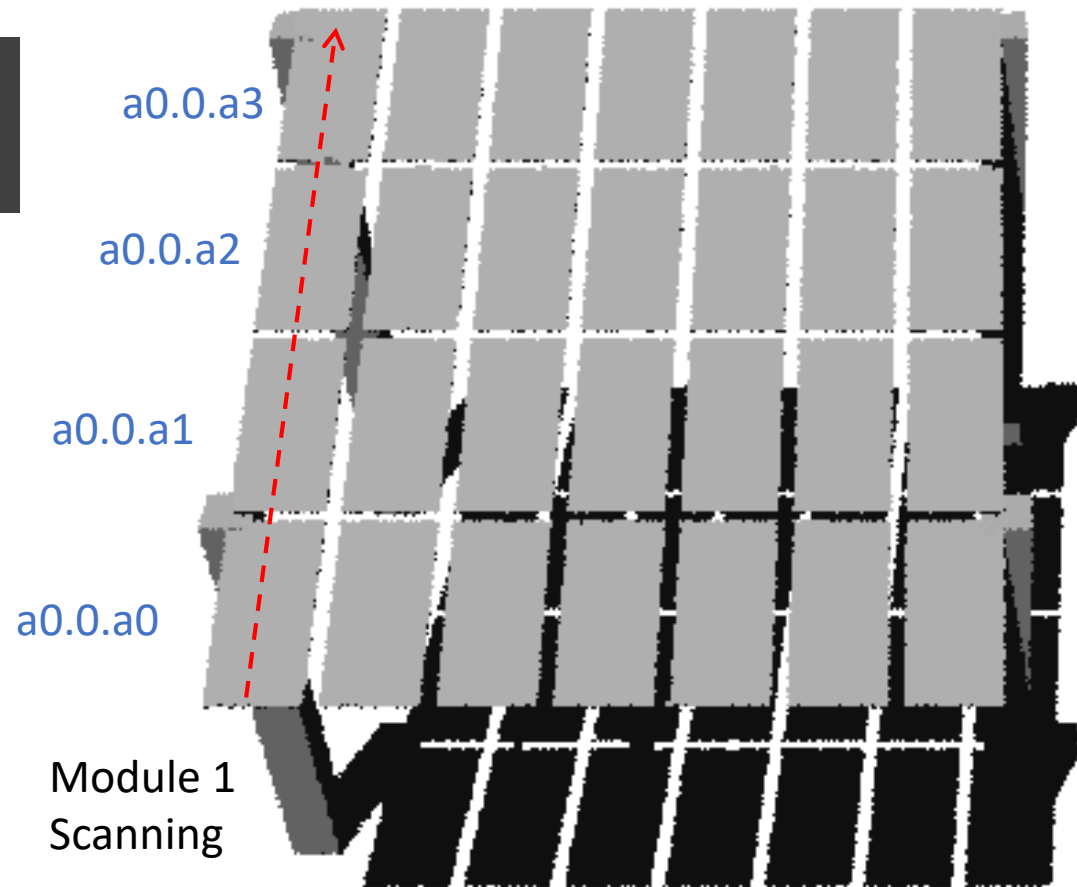
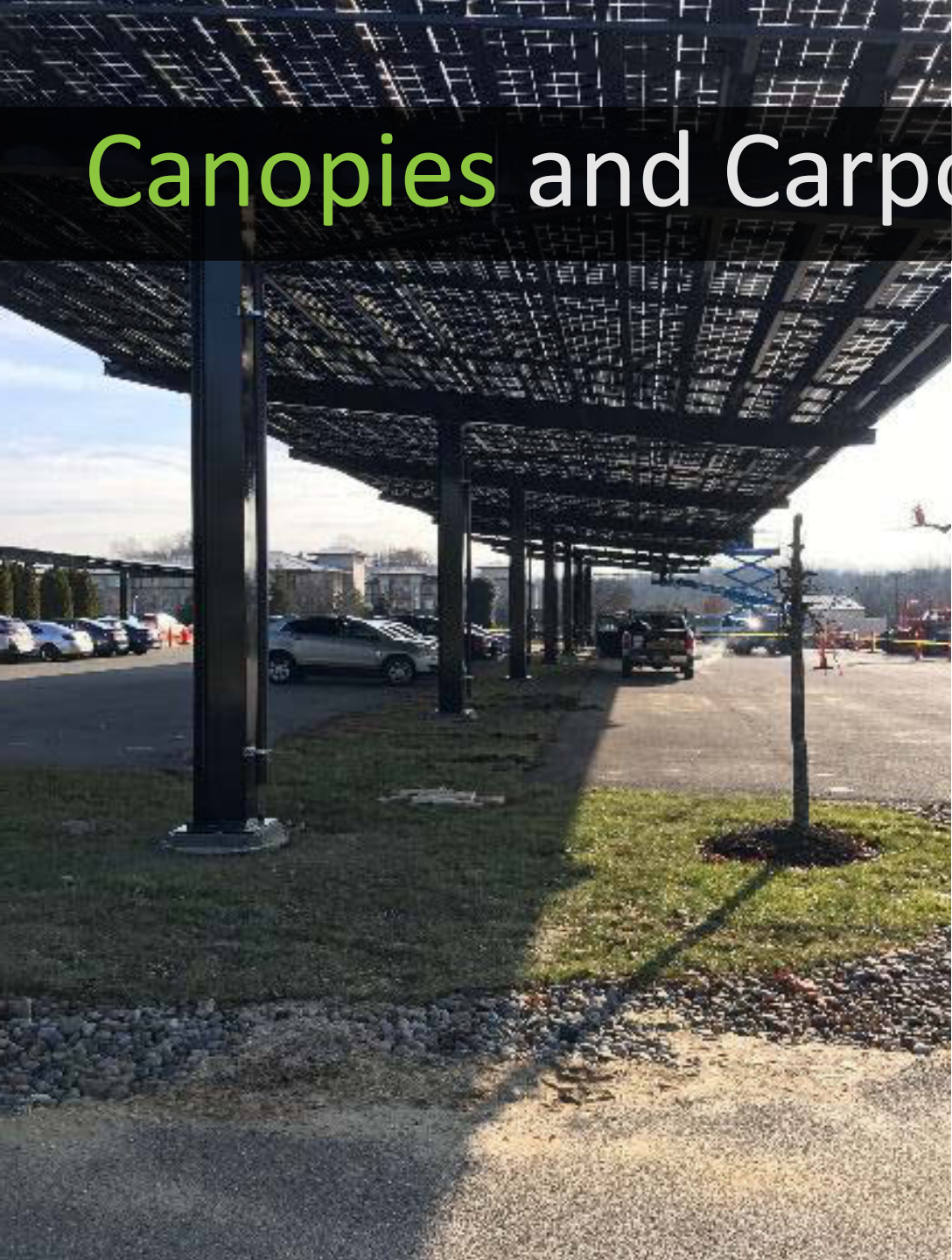


# Canopies and Carports





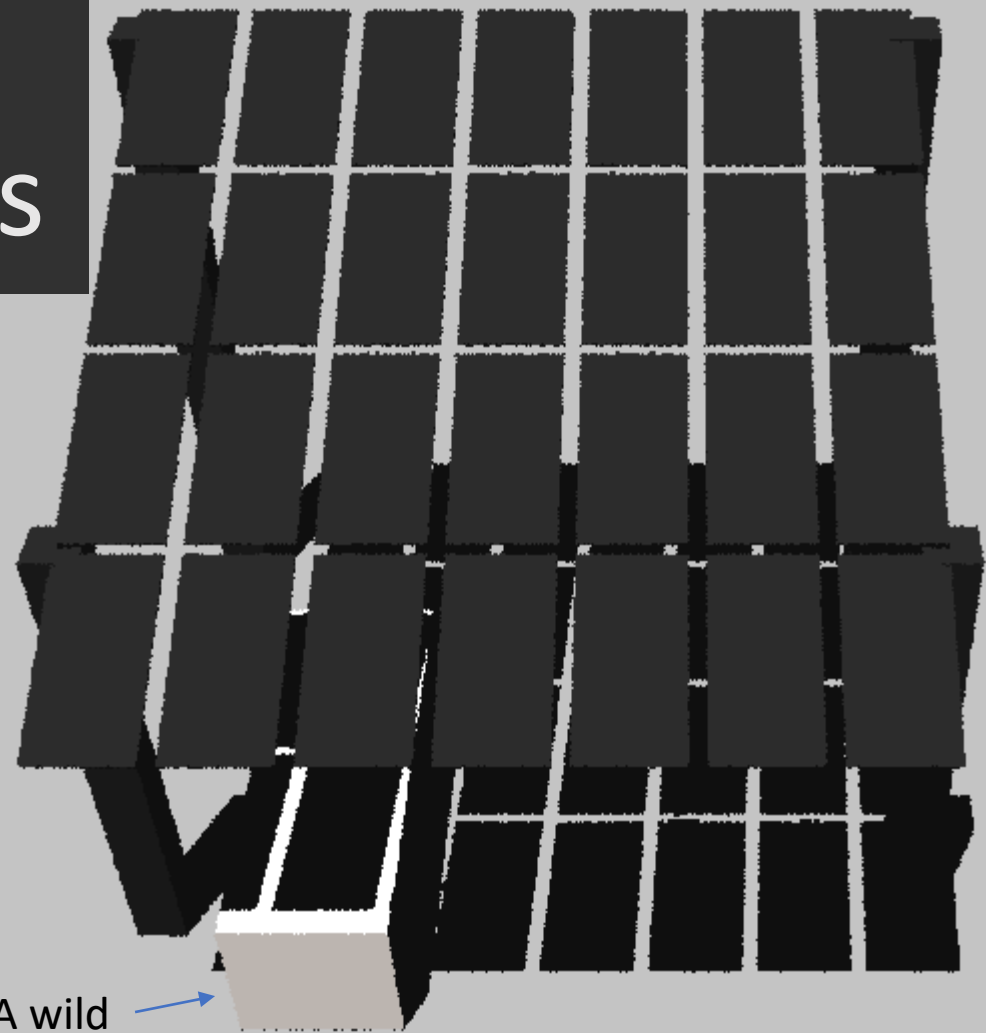
# Canopies and Carports



irr_HotelCaprortMod1.csv									
	x	y	z	rearZ	matttype	rearMat	Wm2Fron	Wm2Back	
3	-3.3	-3.62011	4.42757	4.33757	a0.0.a0.PrismSolar.6457	a0.0.a0.PrismSolar.2310	787.6552	161.1096	
4	-3.3	-3.43446	4.49514	4.40514	a0.0.a0.PrismSolar.6457	a0.0.a0.PrismSolar.2310	787.6781	158.4337	
39	...	...	...	...	...	...	...	...	
40	...	...	...	...	...	...	...	...	
41	-3.3	3.063169	6.860084	6.770084	a0.0.a3.PrismSolar.6457	a0.0.a3.PrismSolar.2310	787.4609	139.0144	
42	-3.3	3.248815	6.927654	6.837654	a0.0.a3.PrismSolar.6457	a0.0.a3.PrismSolar.2310	787.4696	135.2156	
43	-3.3	3.434462	6.995223	6.905223	a0.0.a3.PrismSolar.6457	a0.0.a3.PrismSolar.2310	787.4783	132.7424	
44	-3.3	3.620109	7.062793	6.972793	a0.0.a3.PrismSolar.6457	a0.0.a3.PrismSolar.2310	787.4871	129.142	




# Roofs, Cars, and Different albedo sections



A wild  
white car appears!



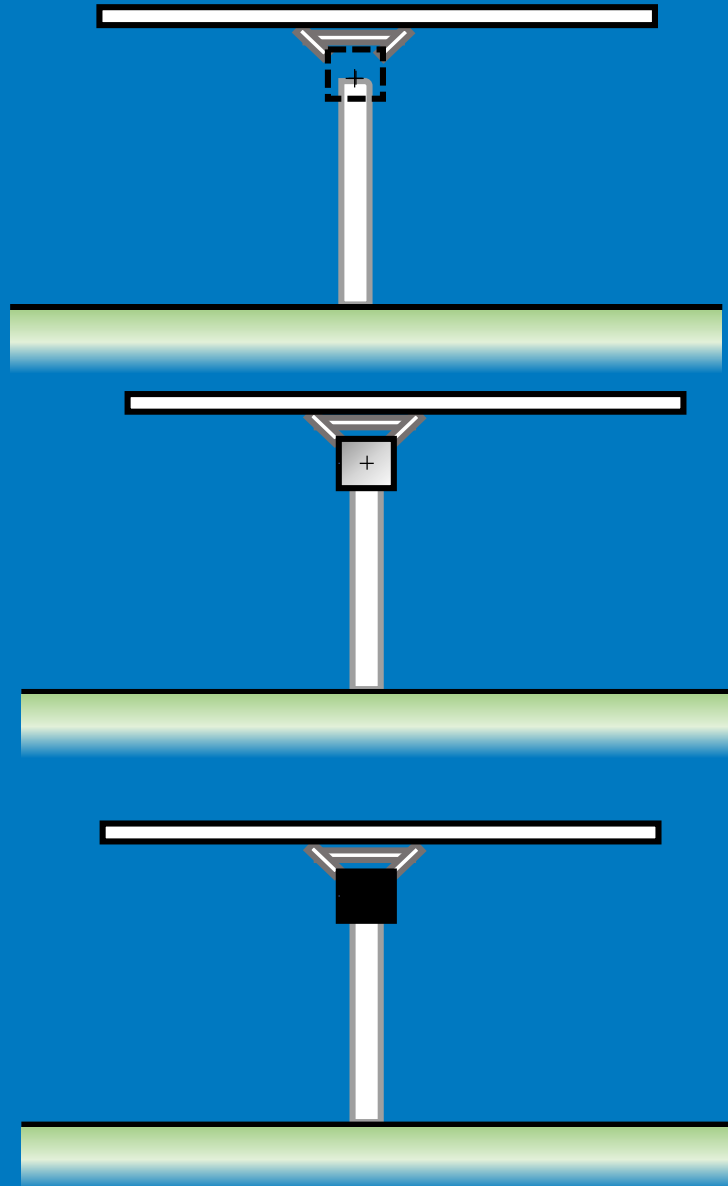


Tracking and Torque tube  
Hourly-yearly simulations  
(a teaser)

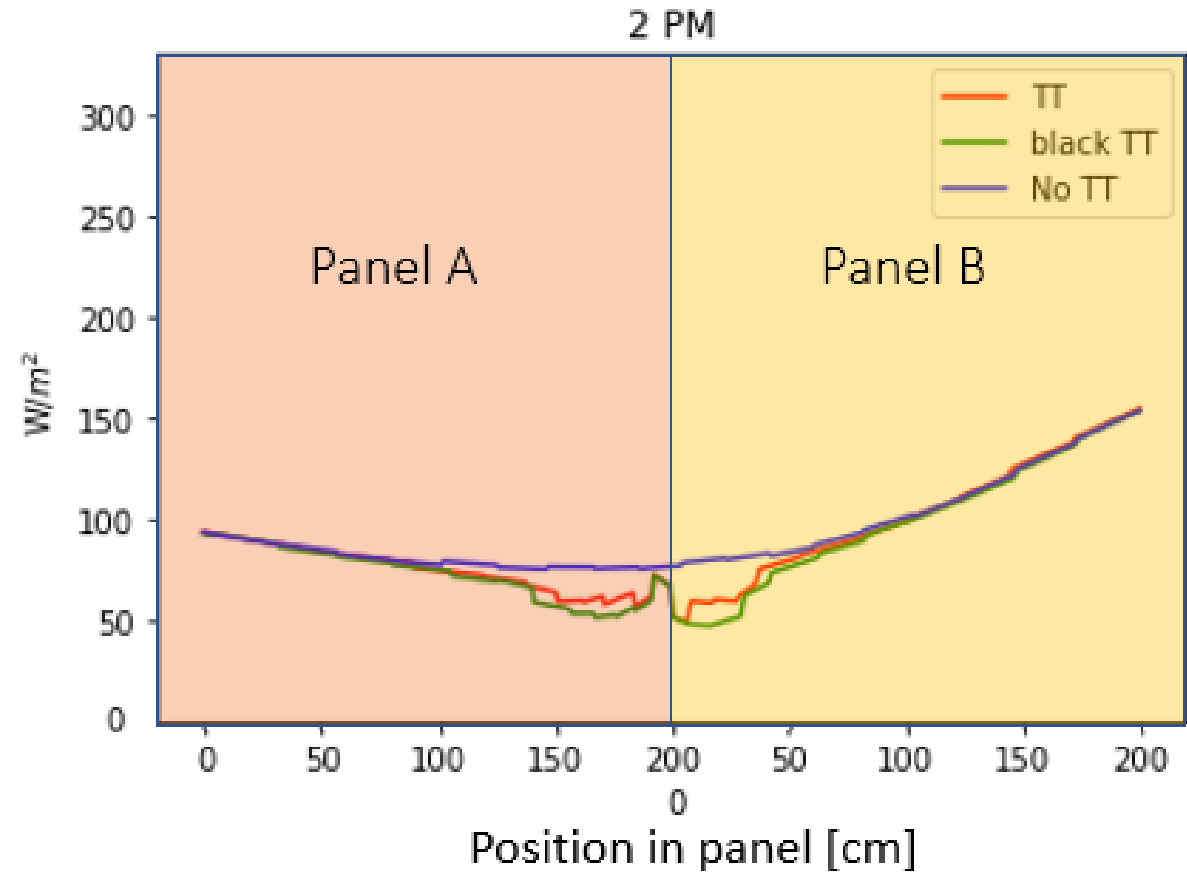




# Varying torquetube reflectivity

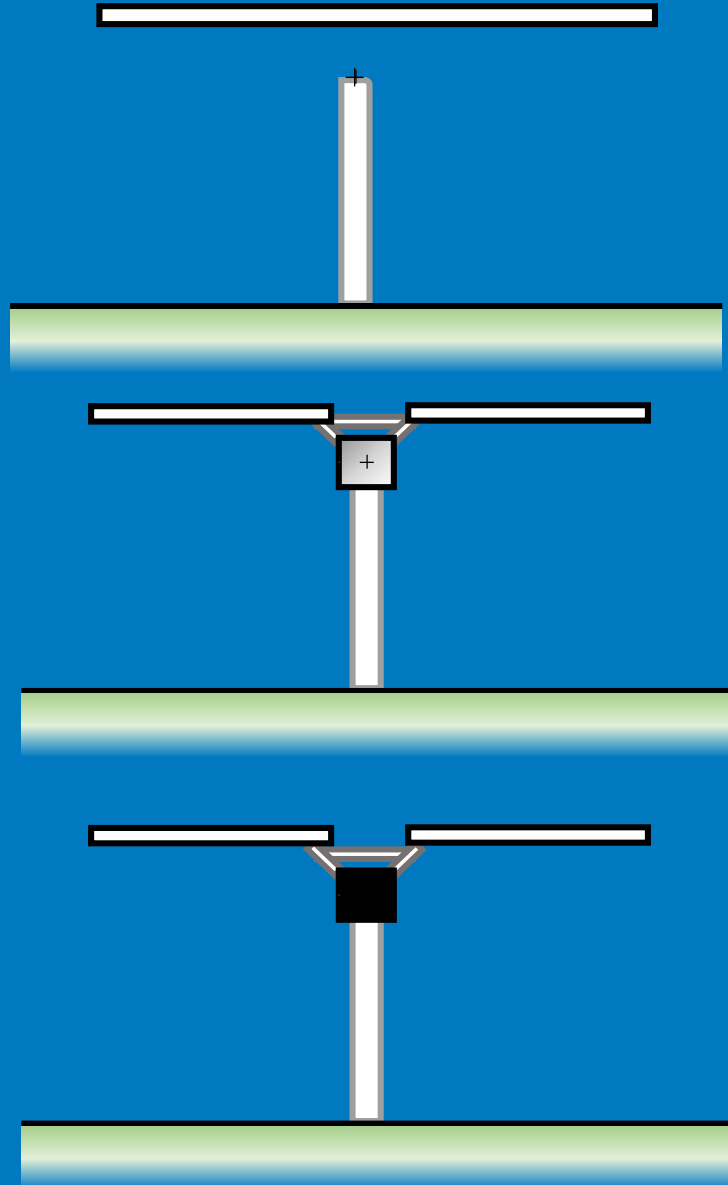


a)

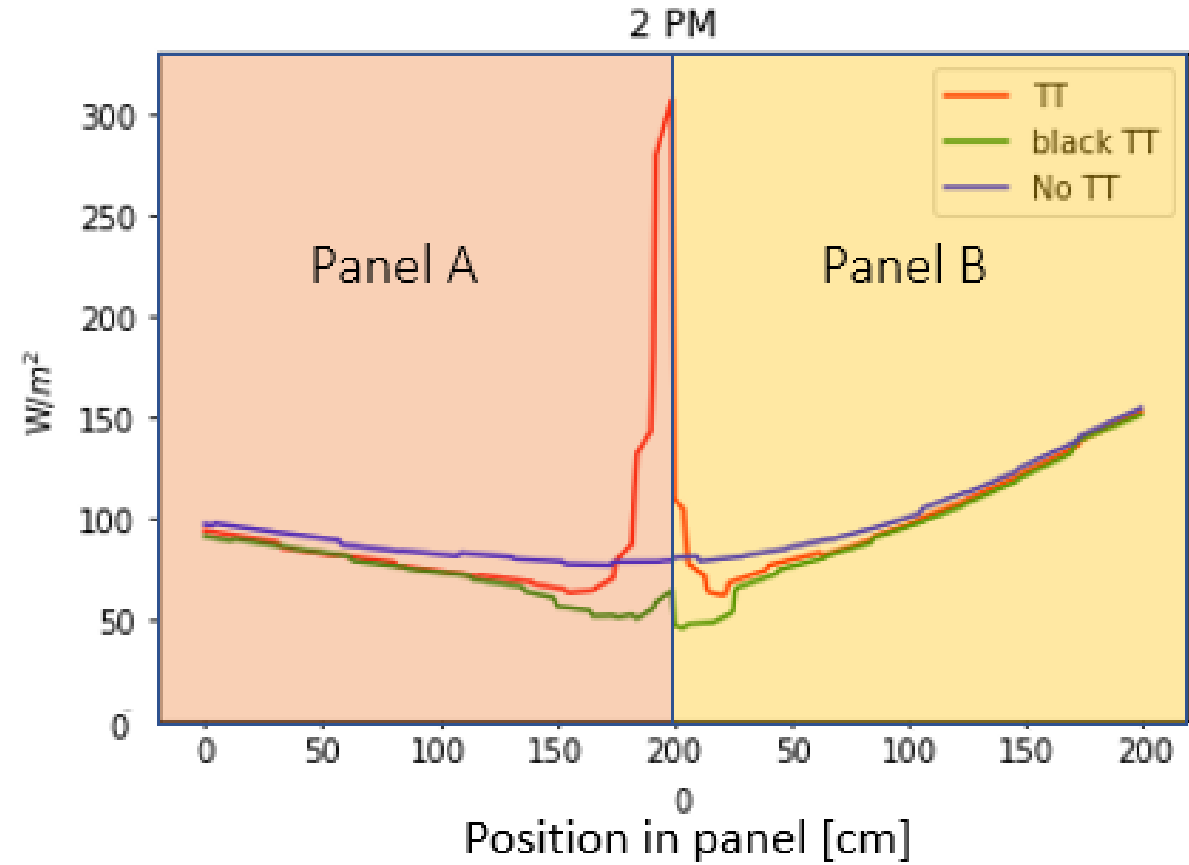


$$\text{Shading factor} = \frac{\sum_{n=0}^N G_{rear} \text{ (no tube)}}{\sum_{n=0}^N G_{rear} \text{ (with tube)}}$$

# Varying torquetube reflectivity



b)



$$\text{Shading factor} = \frac{\sum_{n=0}^N G_{rear} \text{ (no tube)}}{\sum_{n=0}^N G_{rear} \text{ (with tube)}}$$



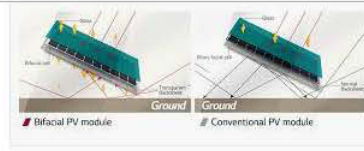
# Torque tube reflections



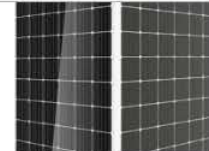
What are bifacial solar modules and how ...  
solarpowerworldonline.com



What are bifacial solar modules and how ...  
solarpowerworldonline.com



Trend to Watch: Bifacial Modules ...  
civicsolar.com



Bifacial solar panels: Breaki...  
solarpowerworldonline.com



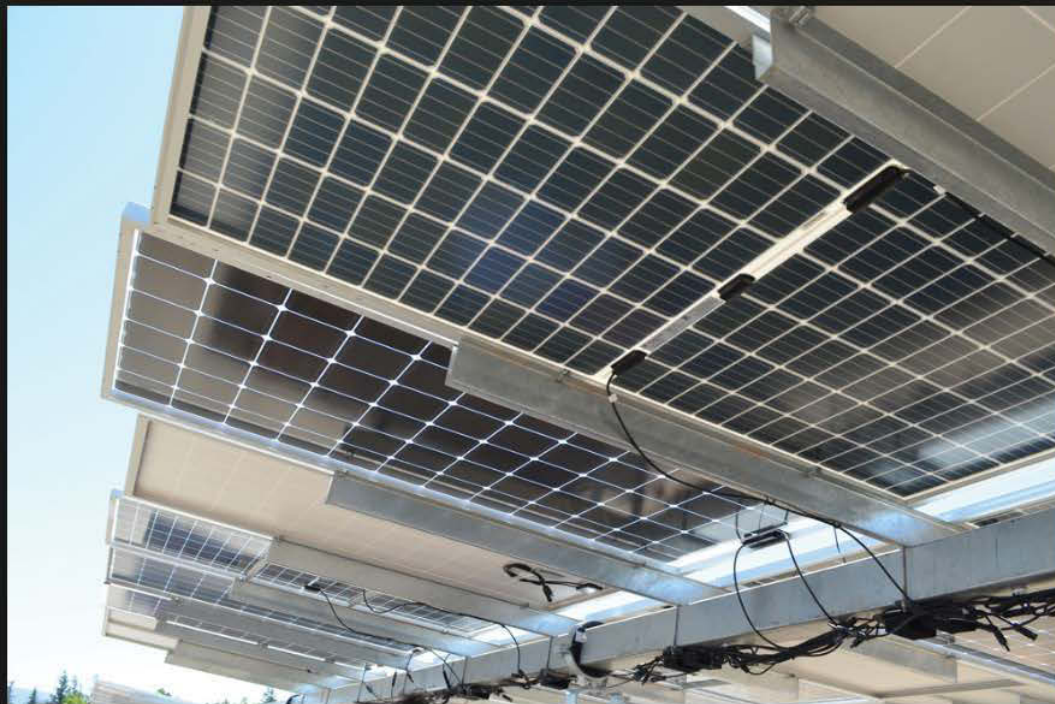
bifacial PERC solar module advances ...  
solarbuildermag.com



Bifacial + NX Horizon = A Winnin...  
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Bifacial Gains: How much will bifacial modules add to solar tracker value? We are about to find out

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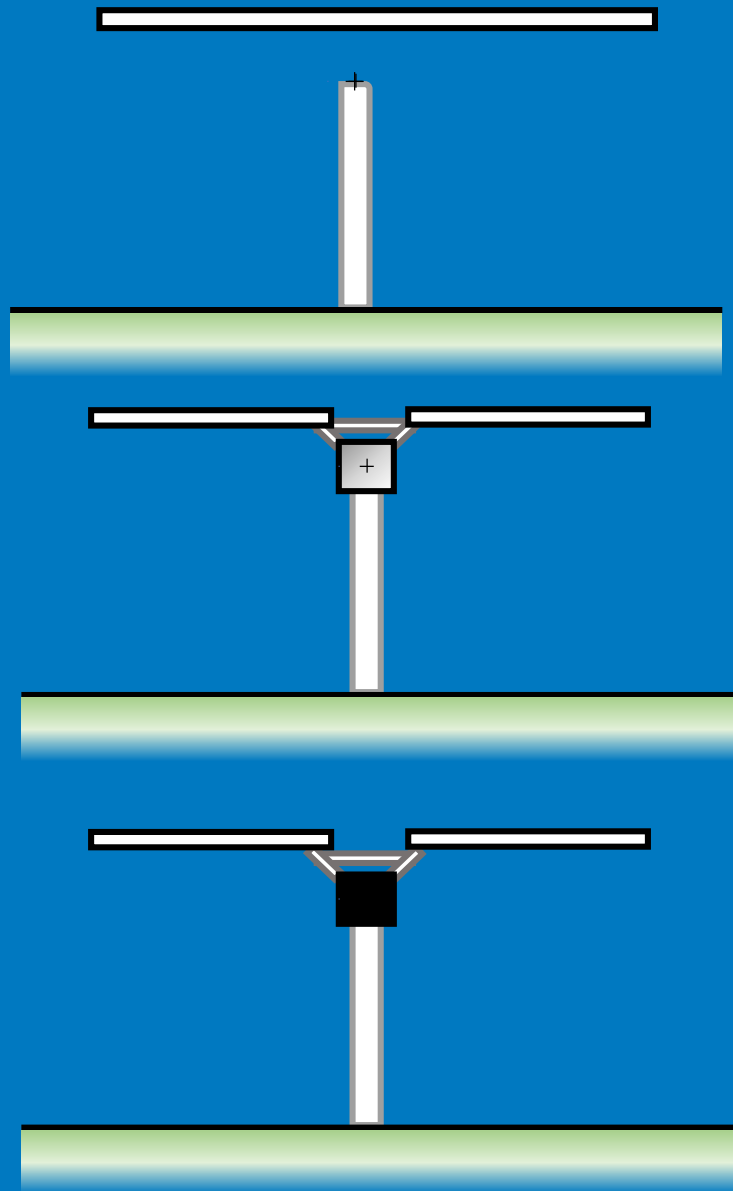
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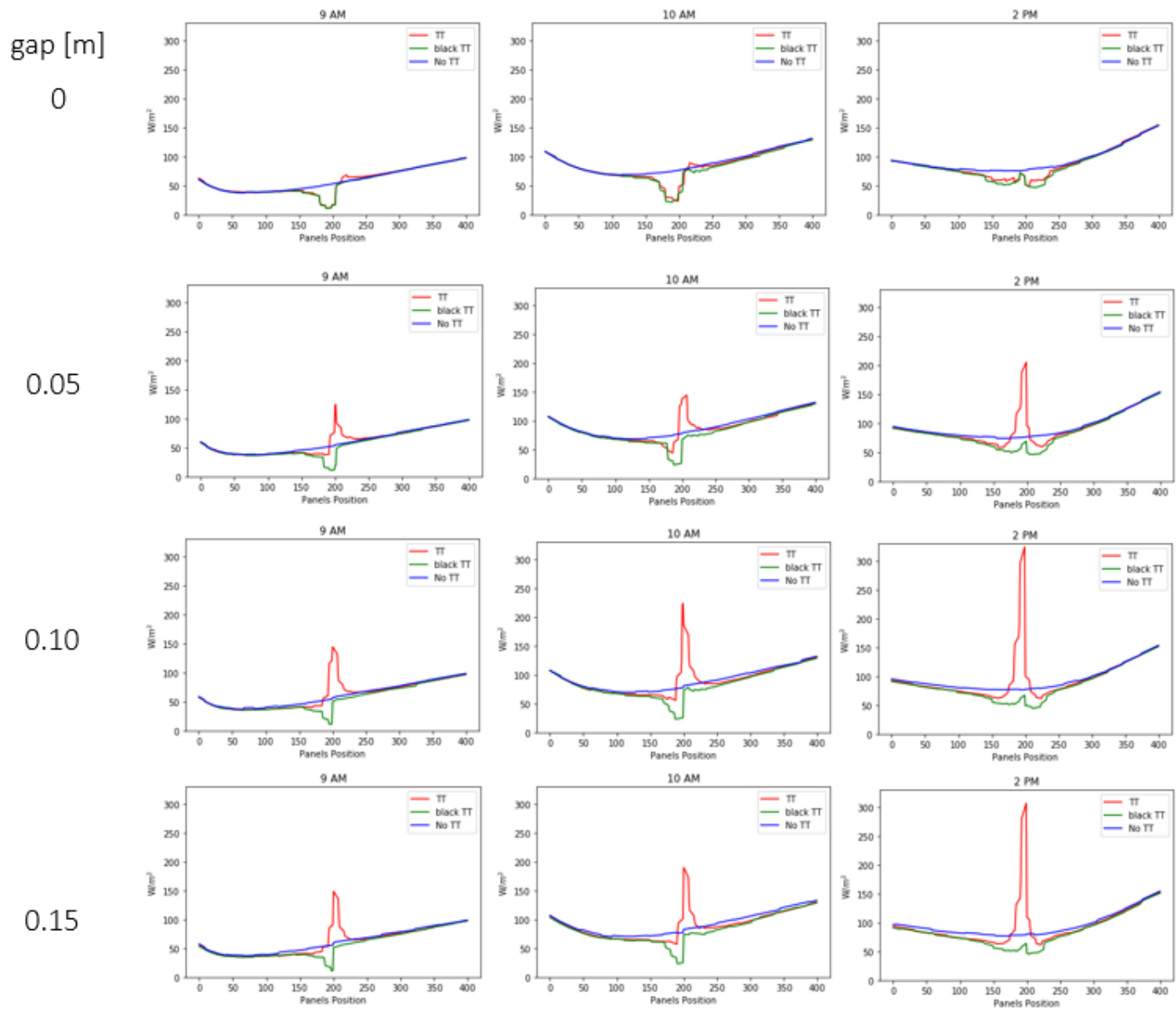


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# Varying torquetube reflectivity



2 UP – 16 JUN Sunny day

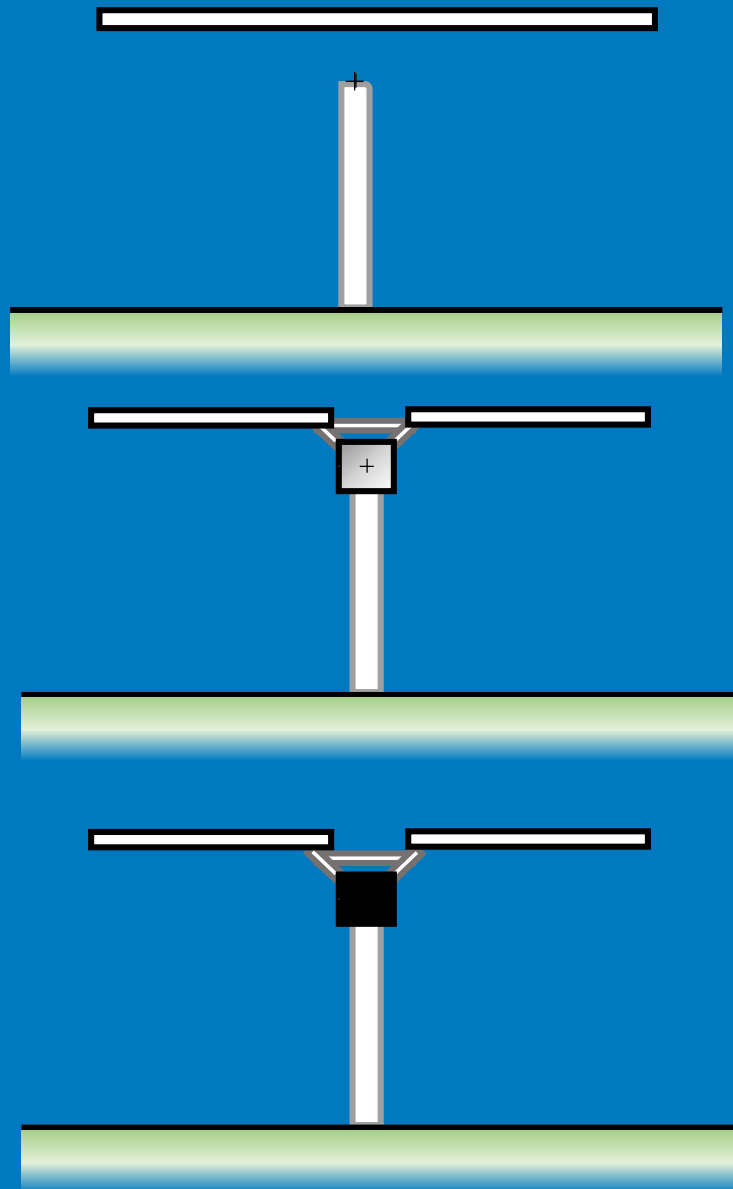


9 am

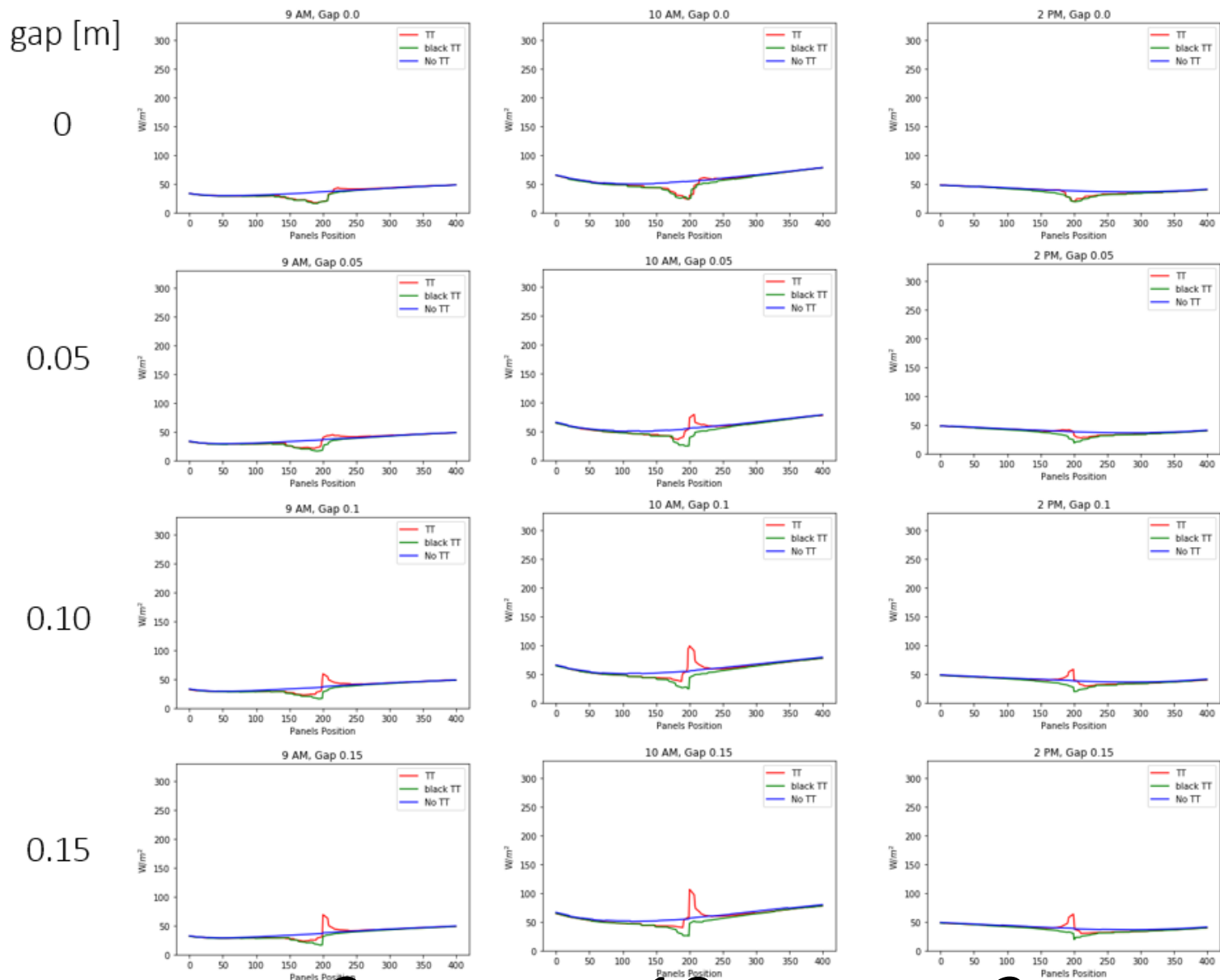
10 am

2 pm

# Varying torquetube reflectivity



2 UP – 10 JUN Cloudy day



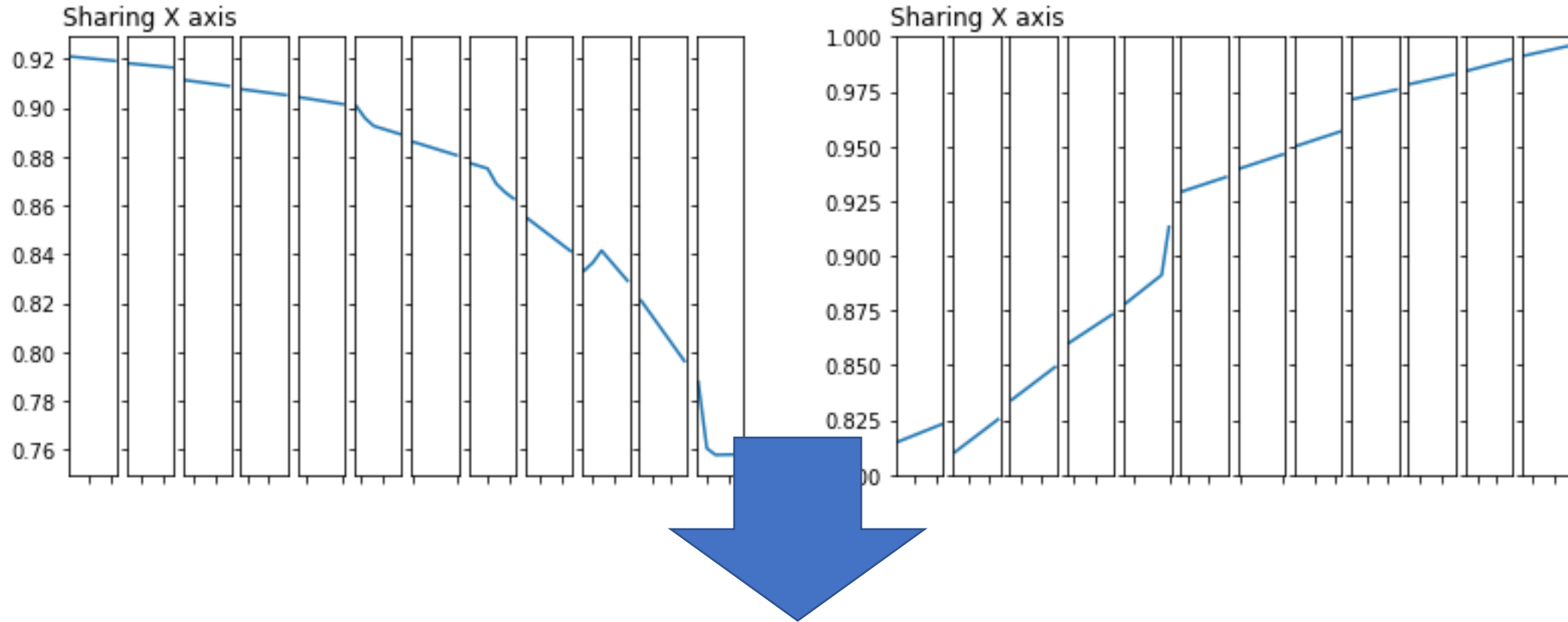
9 am

10 am

2 pm



# Shading to Electrical Mismatch



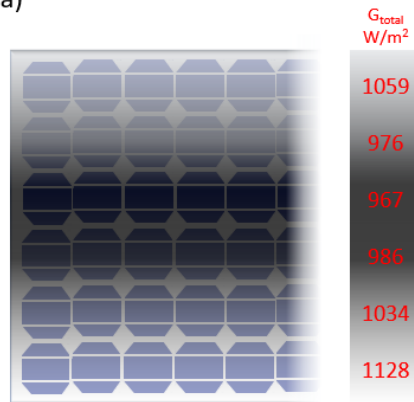
Bifacial radiance **Analysis module**  
ties to PVMismatch

SUNPOWER®

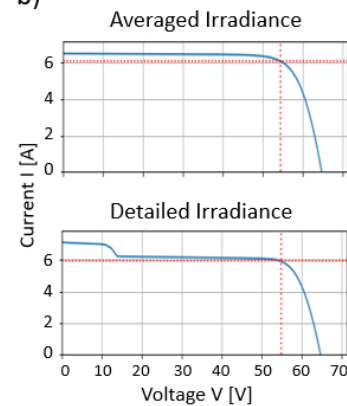
OpenSource!: <https://github.com/SunPower/PVMismatch>

# Electrical Mismatch Model

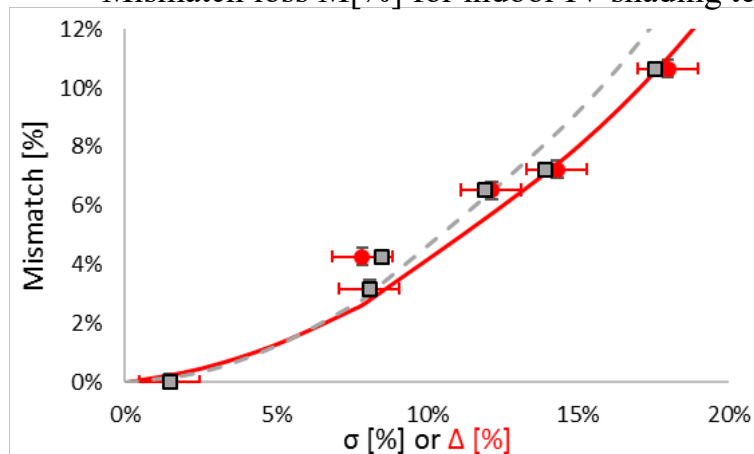
a) Bifacial total irradiance



b) Bifacial mismatch loss calculation



Mismatch loss  $M$  [%] for indoor IV shading tests

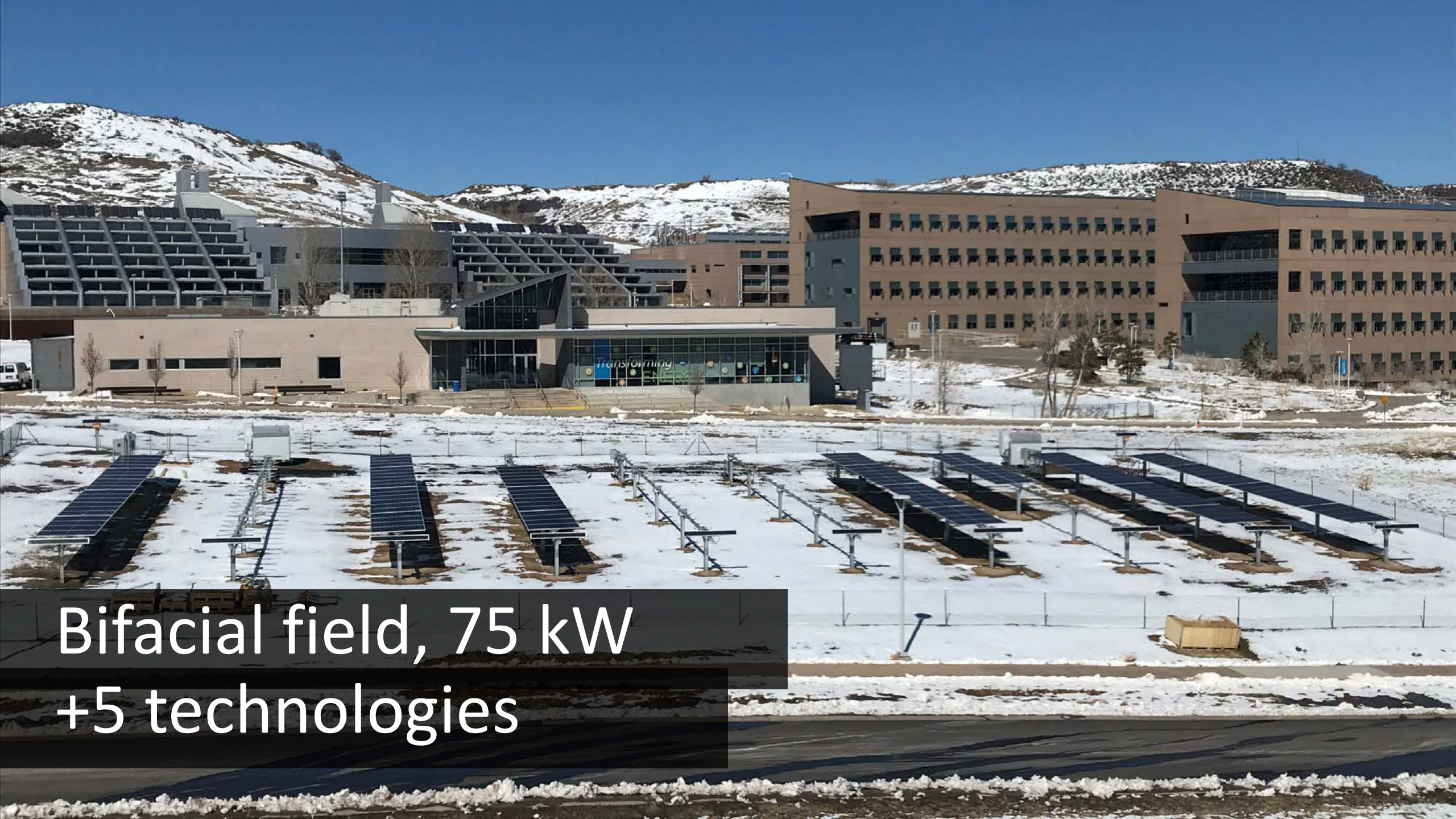


- Front + rear irradiance distribution depends on the mounting and site conditions.
- Irradiance mismatch causes additional loss relative to uniform assumption
- Empirical model provides good fit based on st.dev ( $\sigma$ ) or MAD ( $\Delta$ ) of  $I_{sc}$

$$M[\%]_{Fit1} = e^{1.067 + 1.82 * \ln(\sigma[\%])}$$

$$M[\%]_{Fit3} = 0.12 \Delta[\%] + 2.77 \Delta[\%]^2$$

- EU-PVSEC Oral Paper Accepted

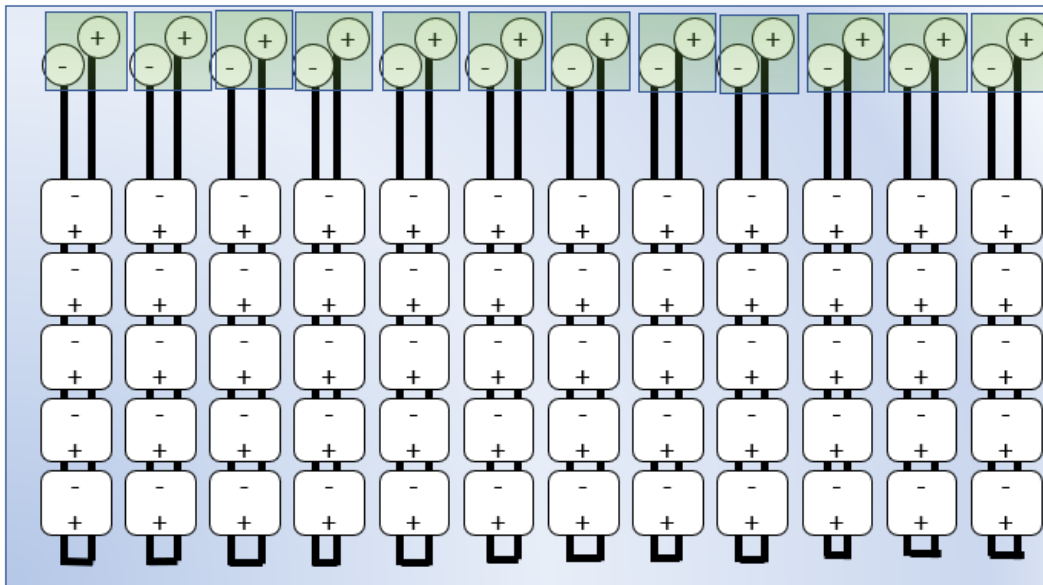


Bifacial field, 75 kW  
+5 technologies



# Electrical Mismatch Model Validation

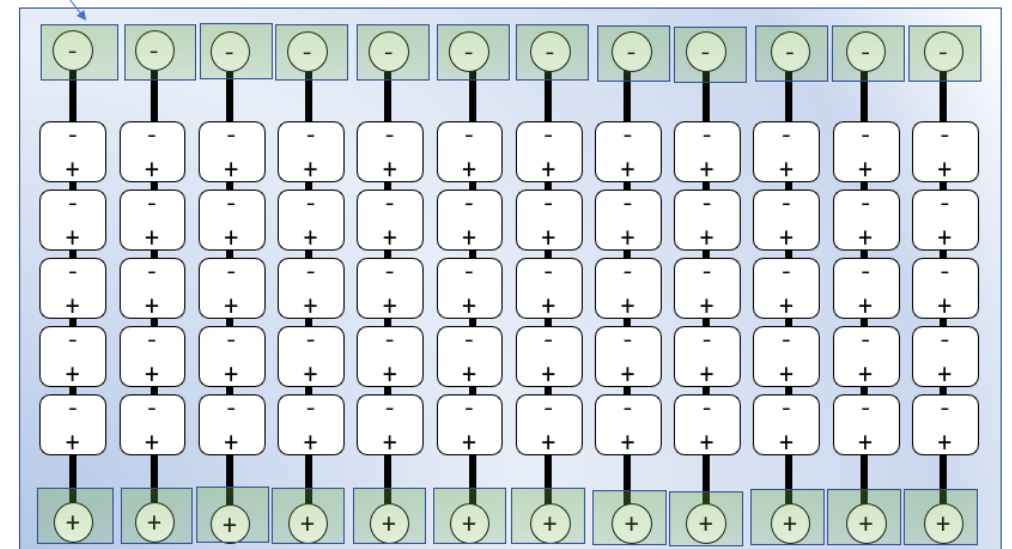
- Custom modules to measure shading loss of Torque Tube
- Strung cross-wise with multiple junction boxes for sub-module Isc measurement



Long Edge, 12 cells

Short Edge, 5 cells (Monofacial)


Junction boxes



Long Edge, 12 cells

Short Edge, 5 cells


# Look for more



May  
14

## 12<sup>th</sup>. PVPMC (Albuquerque)

- New GUI Release
  - Subtleties of modeling bifacial modules.
- 



Jun  
16-20

## 46<sup>th</sup> IEEE PVSC (Chicago)

- Conference plenary talk, Workshop: Overview of bifacial PV status,
  - Oral Session: shading effects on bifacial trackers.
- 



Sep  
12

## 36<sup>th</sup> EU PVSEC (Marseille)

- Oral Session: electrical mismatch and shading.
  - Progress in Photovoltaic journal?
- 



Sep  
17

## 6<sup>th</sup> Bifi PV Workshop (Amsterdam)

- Oral Session: NREL bifacial field measurements of electrical mismatch and shading.
- Oral Session: Albedo updates.

# Conclusions

- Complete overhaul of internal geometry creation.
  - Improved scanning functions.
  - Cell level module creation enabled.
  - Many customization options of the geometry in response to identified needs of industry and research.
  - Appending of terrain, structures and things made easier.
- (currently) Streamlining functions and input parameters for seamless interaction with GUI, HPC and regular use.
- Analysis functions, tying with PVMismatch.
- Ongoing work to calculate and relate shading loss and electrical mismatch.
- Doing validation with real systems (need more! E-mail us for collaborations)
- Need beta-testers for GUI and software. Jupyter journals, youtube videos and support available 😊



# Thank you

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[www.nrel.gov](http://www.nrel.gov)

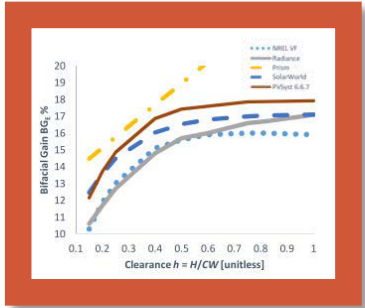
[Silvana.Ayala@nrel.gov](mailto:Silvana.Ayala@nrel.gov)

NREL/PR-5K00-74009

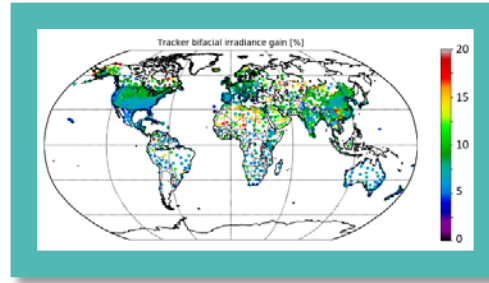
**A portion of the research was performed using computational resources sponsored by the Department of Energy's Office of Energy Efficiency and Renewable Energy and located at the National Renewable Energy Laboratory.**

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Single-axis tracking model



Albedo database



Assess system performance impact from rear irradiance shading and electrical mismatch

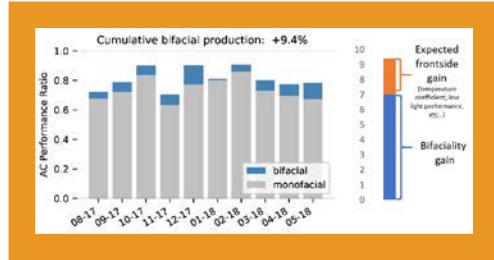


2017

Comparison of models and validation with test-bed data



2018



Framework to calculate bifacial gain with field data

2019

Standards for bifacial rating

