Mismatch loss in bifacial modules due to non-uniform illumination in 1D tracking systems

IEEE PVSC
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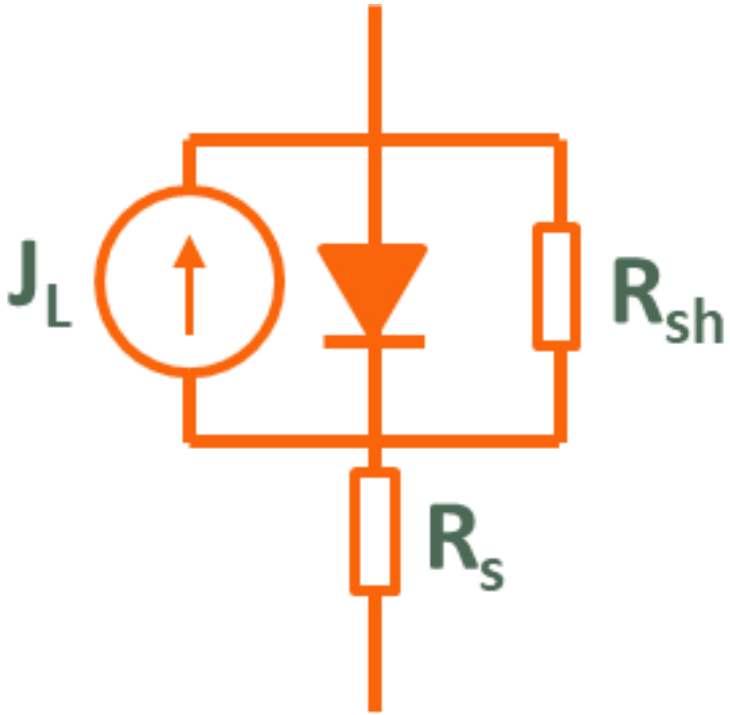
Jenya Meydbray, PV Evolution Labs

Image from https://www.nextracker.com

Equivalent circuit of a PV module

Equivalent circuit of a PV module



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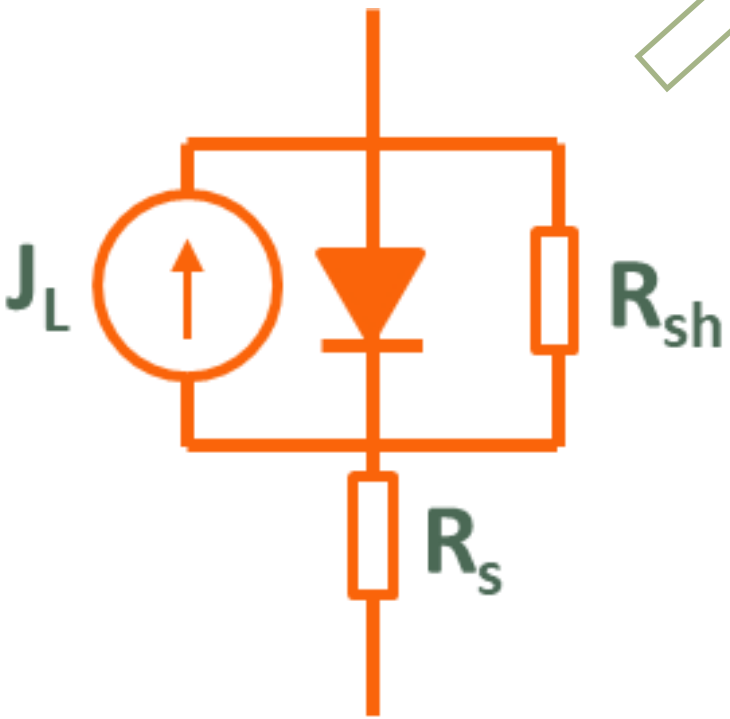

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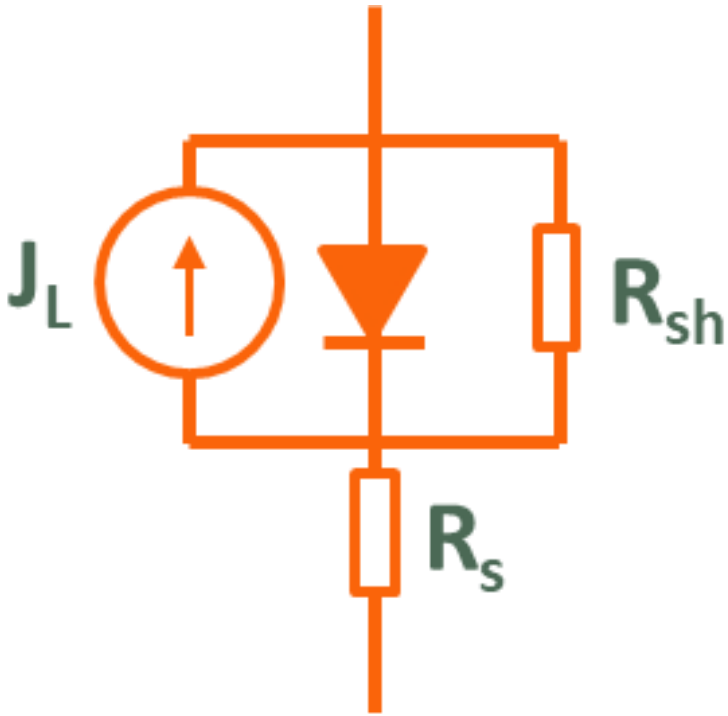

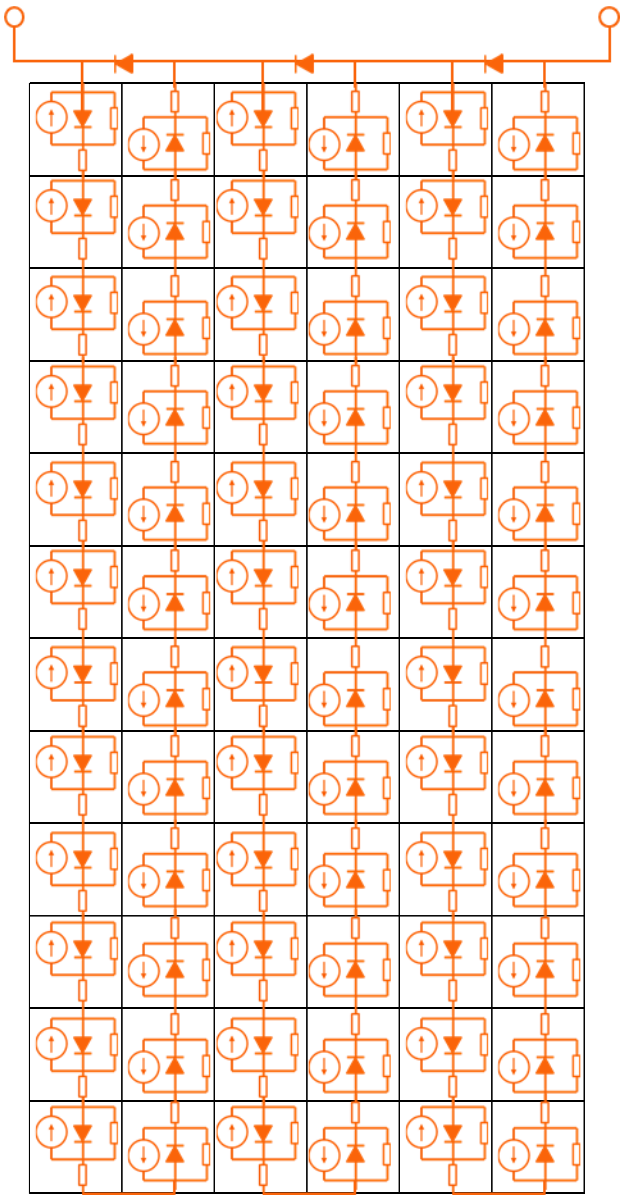

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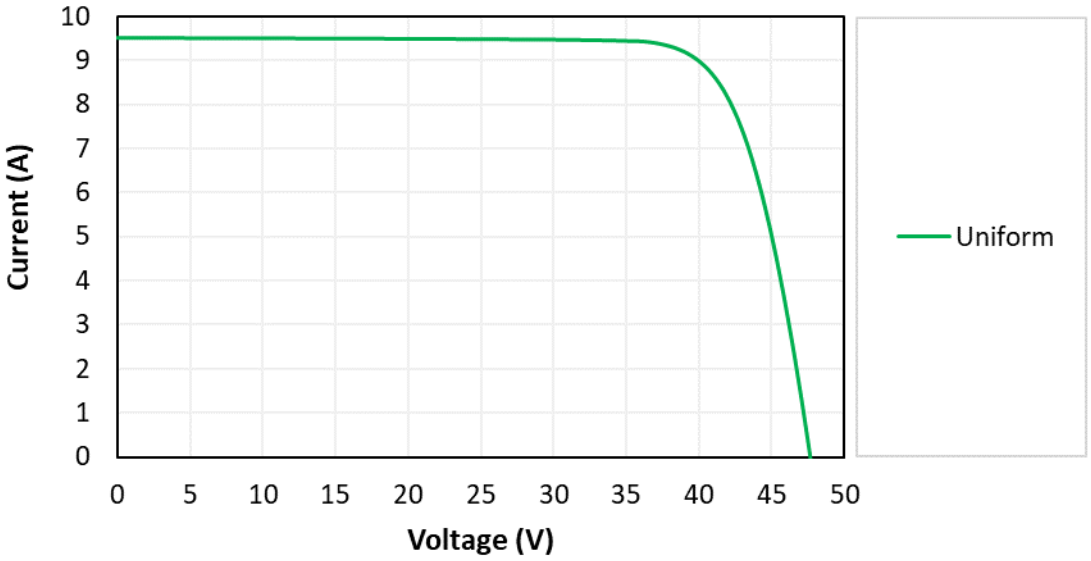
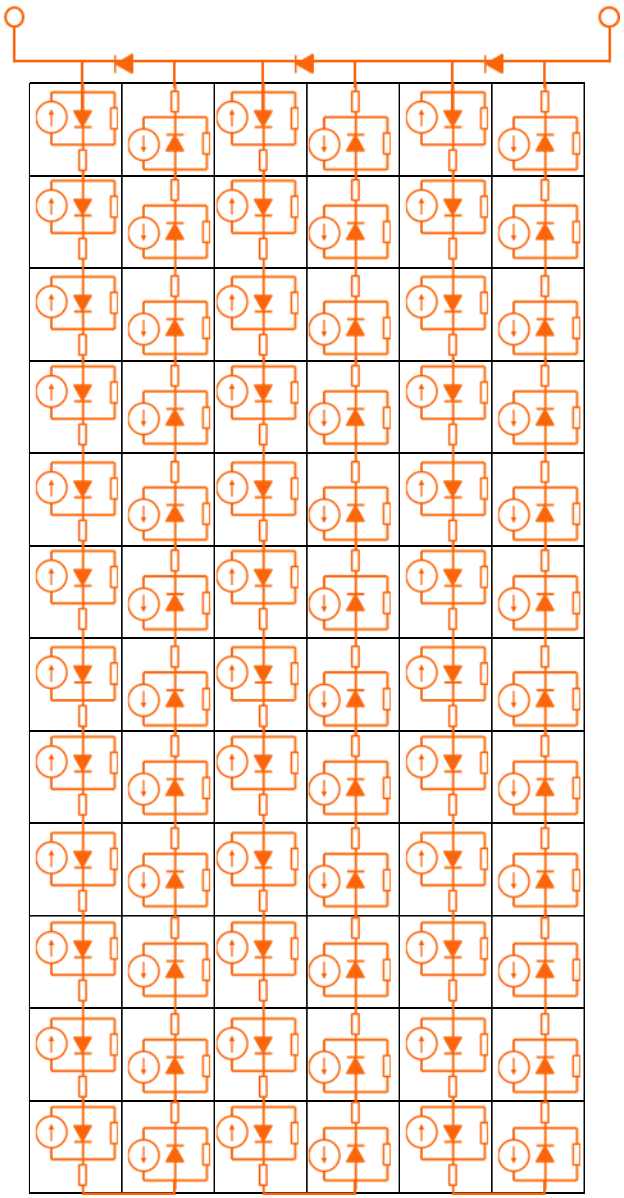
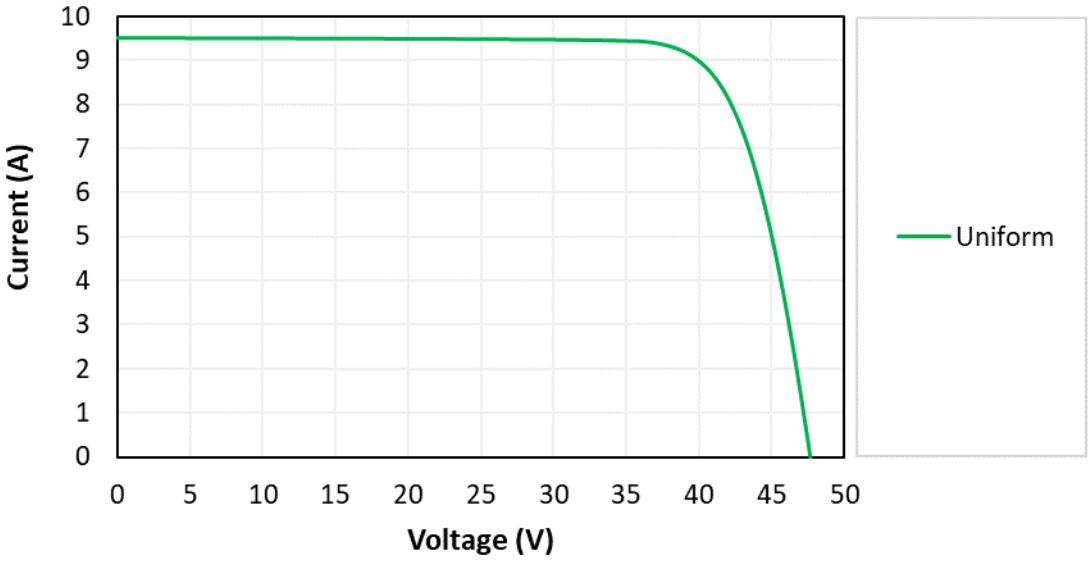




SPICE solver gives module's IV curve

Equivalent circuit of a PV module

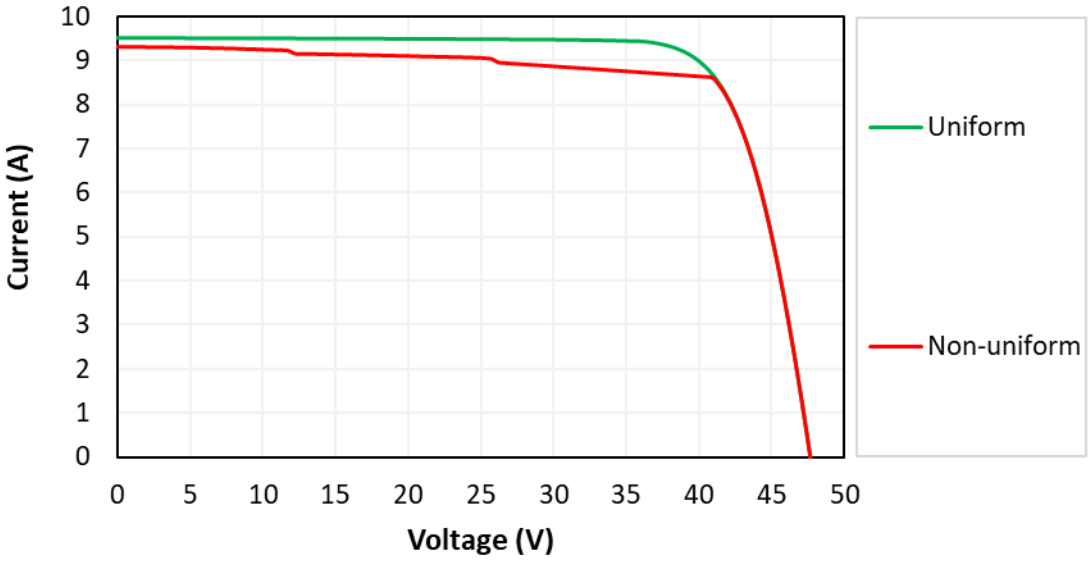


No cell-to-cell mismatch loss

Highly uniform

0.1%	-0.7%	0.4%	0.0%	0.0%	-0.1%
0.0%	-0.9%	-0.4%	-0.1%	0.0%	-0.2%
-0.2%	0.3%	0.1%	0.3%	0.0%	0.6%
0.2%	-0.1%	-0.4%	-0.1%	0.0%	-0.2%
-0.1%	0.0%	0.4%	-0.2%	0.2%	-0.2%
-0.2%	0.7%	-0.3%	0.1%	-0.5%	0.1%
-0.1%	0.8%	0.4%	0.3%	-0.1%	0.1%
-0.3%	-0.5%	0.1%	0.0%	0.3%	-0.1%
0.2%	0.1%	-0.3%	0.1%	-0.1%	0.2%
0.2%	0.7%	-0.5%	-0.3%	-0.5%	0.4%
0.1%	-0.1%	0.1%	0.2%	-0.8%	0.1%
0.3%	0.0%	0.1%	0.0%	-0.4%	-0.5%

Equivalent circuit of a PV module

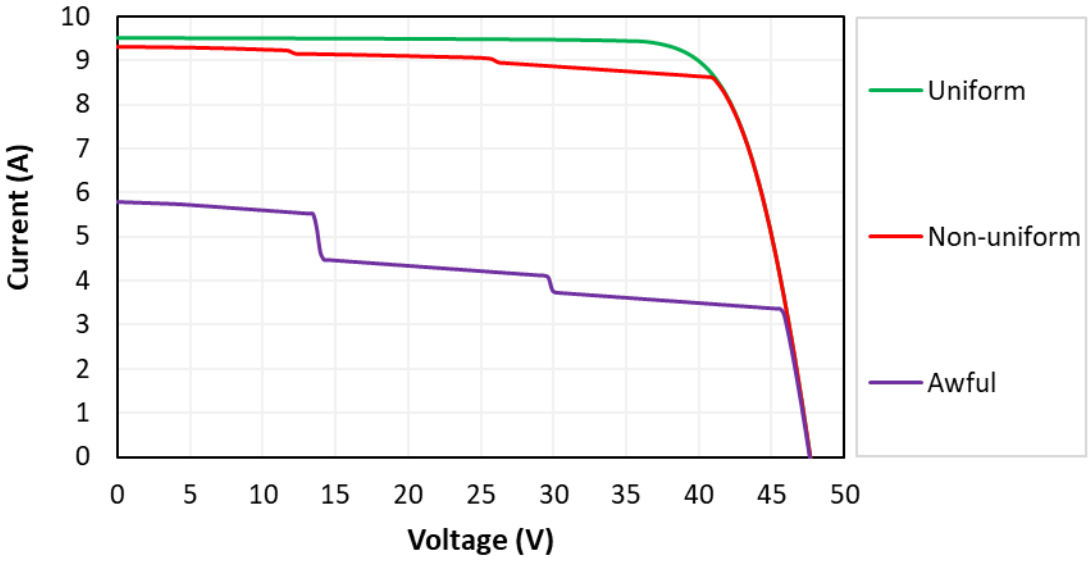


Significant cell-to-cell mismatch loss

Non-uniform

4.8%	-2.4%	0.5%	1.7%	0.2%	0.1%
-1.3%	-1.0%	-1.0%	-3.3%	2.6%	1.8%
0.7%	3.9%	1.2%	0.3%	-4.2%	-0.8%
-2.6%	2.8%	0.9%	-1.2%	5.2%	-4.4%
-2.4%	-1.1%	3.6%	-5.0%	3.5%	-9.4%
1.7%	-0.7%	3.1%	2.6%	-5.0%	1.6%
-3.1%	-0.2%	0.6%	-1.5%	-0.6%	1.2%
-0.9%	-3.0%	-4.1%	-3.6%	2.7%	4.7%
2.1%	6.1%	-1.3%	-4.8%	1.9%	2.0%
3.8%	5.4%	-4.8%	0.7%	1.0%	-1.4%
-2.3%	-2.4%	-1.4%	-0.5%	3.7%	-4.2%
1.9%	3.0%	-3.8%	2.4%	-1.0%	2.4%

Equivalent circuit of a PV module

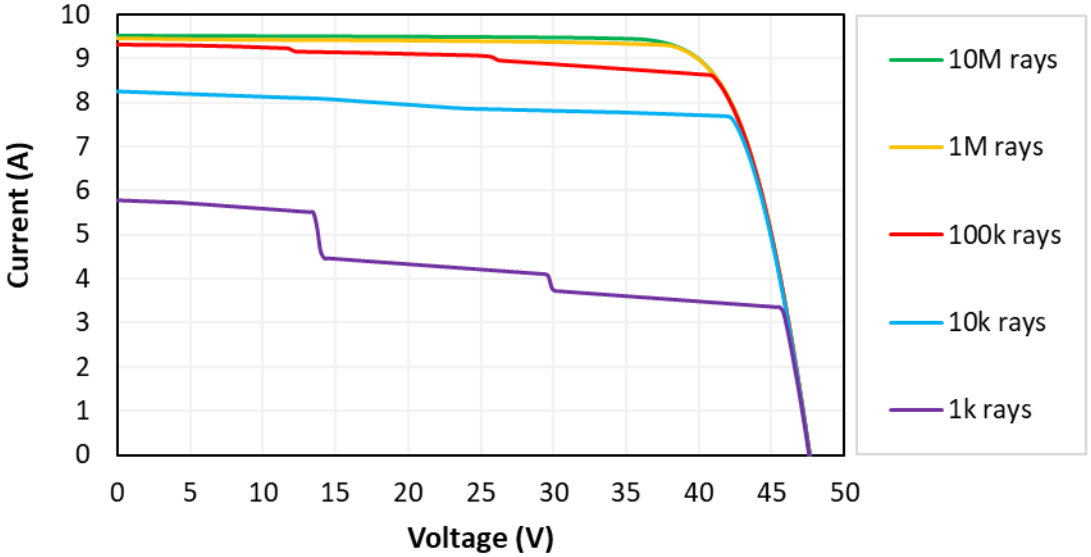


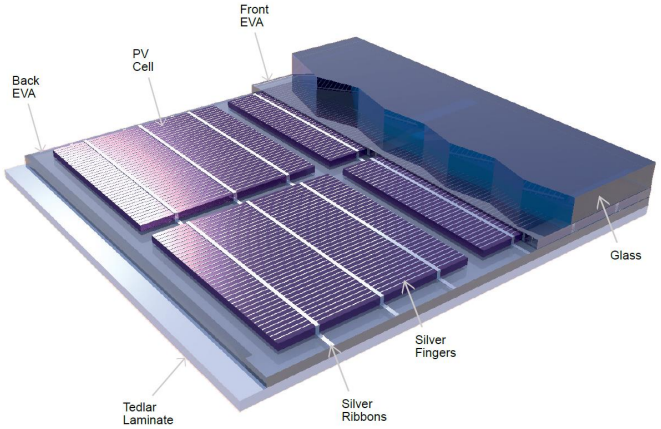
Awful cell-to-cell mismatch loss

Awfully non-uniform

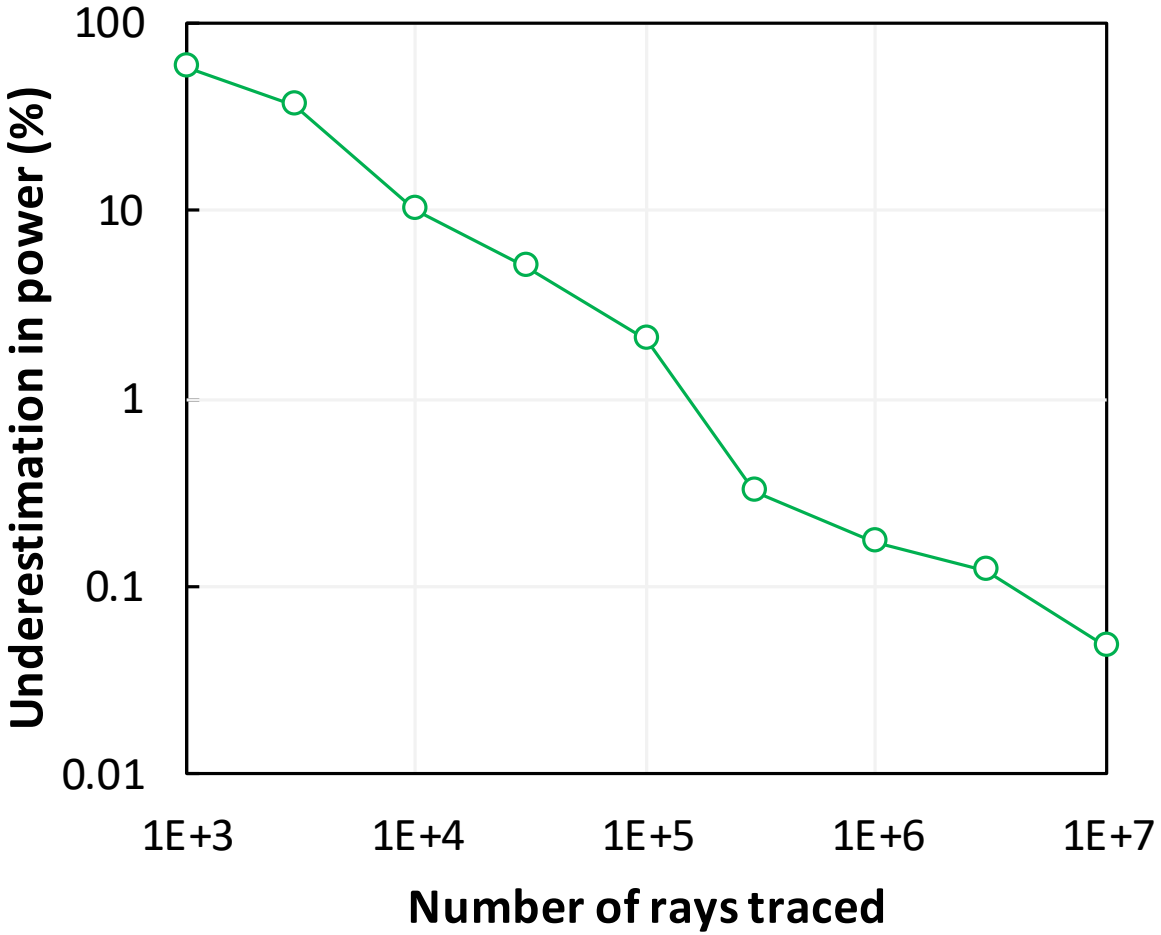
23.3%	-31.2%	17.2%	28.0%	25.1%	-36.9%
8.5%	11.1%	55.3%	14.2%	2.2%	22.3%
-6.0%	35.9%	-28.4%	37.7%	-25.7%	-24.3%
-42.7%	55.7%	-23.9%	-1.4%	-8.3%	45.9%
-30.3%	62.8%	33.8%	-58.4%	-5.4%	-41.9%
-28.2%	2.9%	-18.4%	-29.4%	-27.1%	58.3%
62.7%	21.2%	-9.1%	29.0%	13.9%	70.6%
-26.0%	30.0%	-40.3%	-50.1%	-34.9%	19.1%
-36.3%	26.7%	-8.5%	5.6%	-24.2%	3.7%
-27.4%	-66.0%	-39.4%	42.6%	-7.4%	-27.9%
-27.4%	44.6%	-22.8%	12.5%	10.2%	6.3%
-5.3%	-28.9%	4.4%	33.0%	-12.8%	-44.1%

Equivalent circuit of a PV module



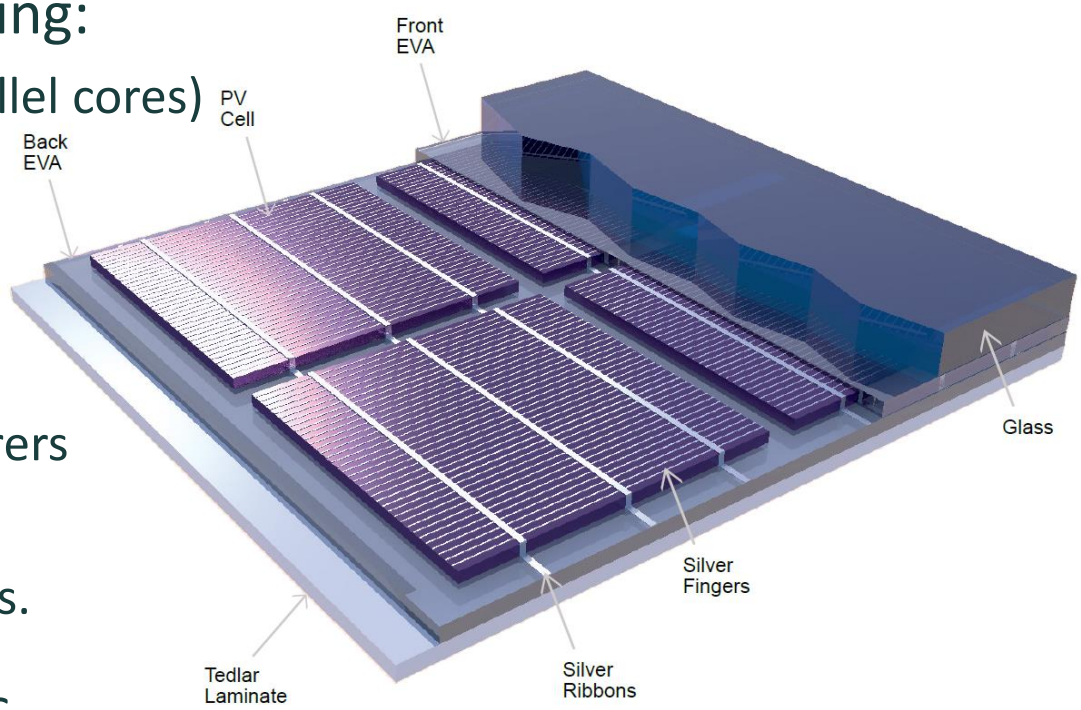


Mismatch loss due to insufficient rays



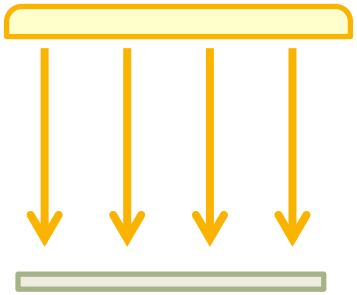
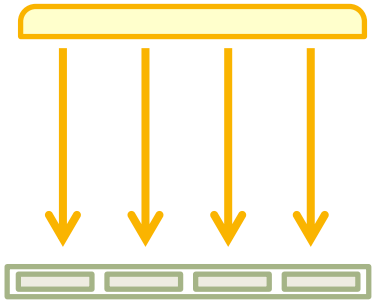
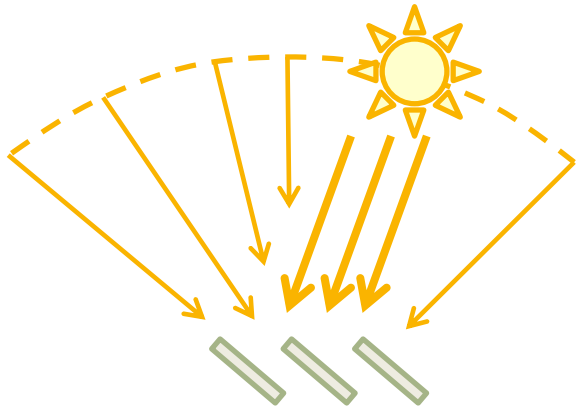
SunSolve™

- Inputs are material properties and geometries.
- Optics solved by ray tracing:
  - cloud-based (≤ 2000 parallel cores)
  - optimized physics solver
  - extremely fast.
- Widely used by
  - tier 1 module manufacturers
  - materials companies
  - leading research institutes.

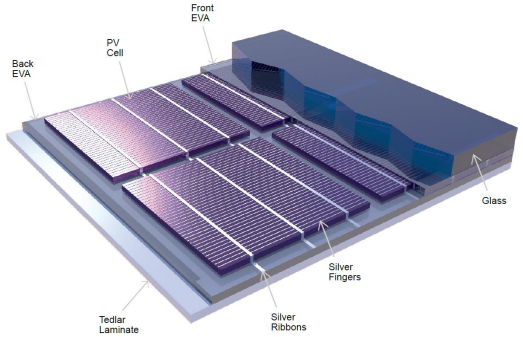


- Expanded for PV systems
  - Ground, torque-tube, system configuration, backtracking
  - SPICE to solve module circuit
  - Temperature model

Measurement conditions

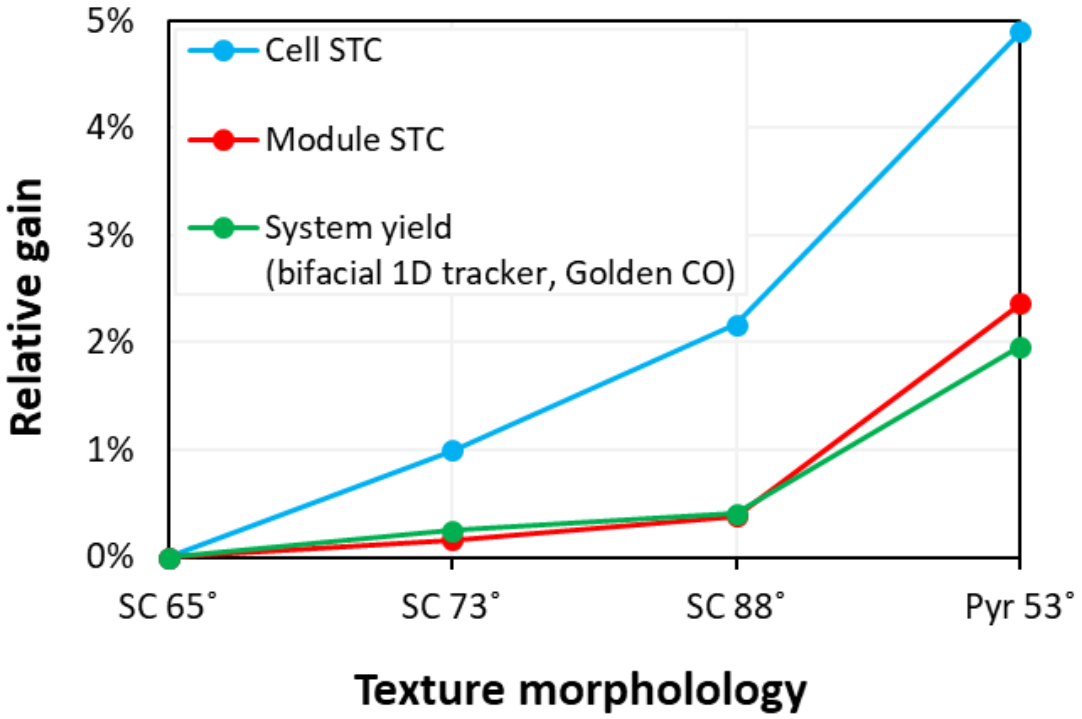
Solar cell	Module	System
STC	STC	No standard
		
$\theta = 0^{\circ}$	$\theta = 0^{\circ}$	$\theta = 0 – 90^{\circ}$
AM1.5g	AM1.5g	Variable spectrum
G = 1000 W/m^2	G = 1000 W/m^2	G = 0 – 1100 W/m^2 ?
T = 25 ˚C	T = 25 ˚C	T = –10 – 75 ˚C ?
seconds	seconds	weeks – year
$	$$$$$$$$$$$$$$$$$$	$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$ $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

SunSolve™



Example: Isotexture vs black silicon vs pyramids

Paper 855: Friday 9:30 AM, Area 4
Malcolm Abbott *et al.*
"Annual energy yield analysis of solar cell technology"



Systems investigated

- Bifacial.
- 1D tracking, NS axis
- One-high & two-high

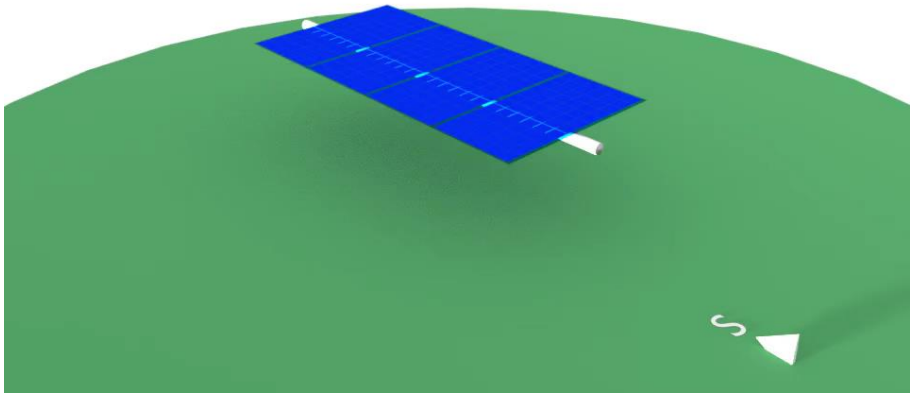
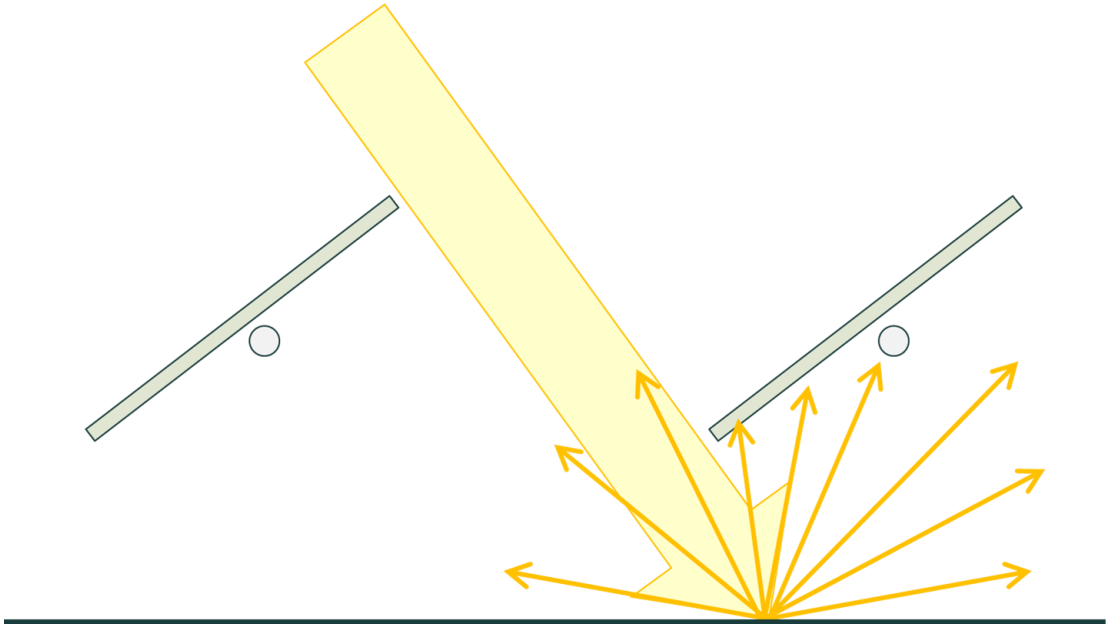


Image from https://www.nextracker.com

Image from https://www.pv-magazine.com

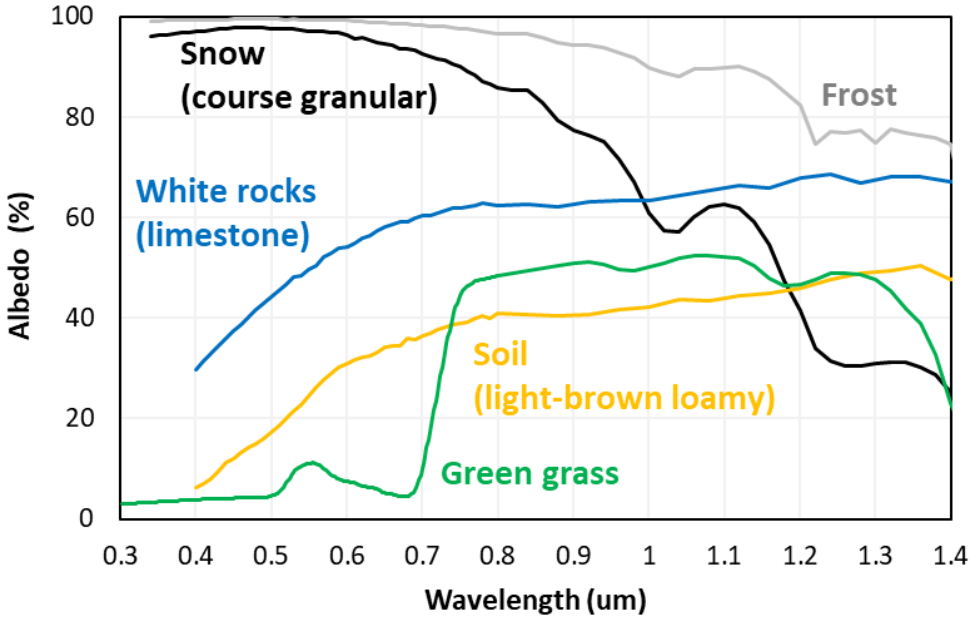
Complications of rear illumination

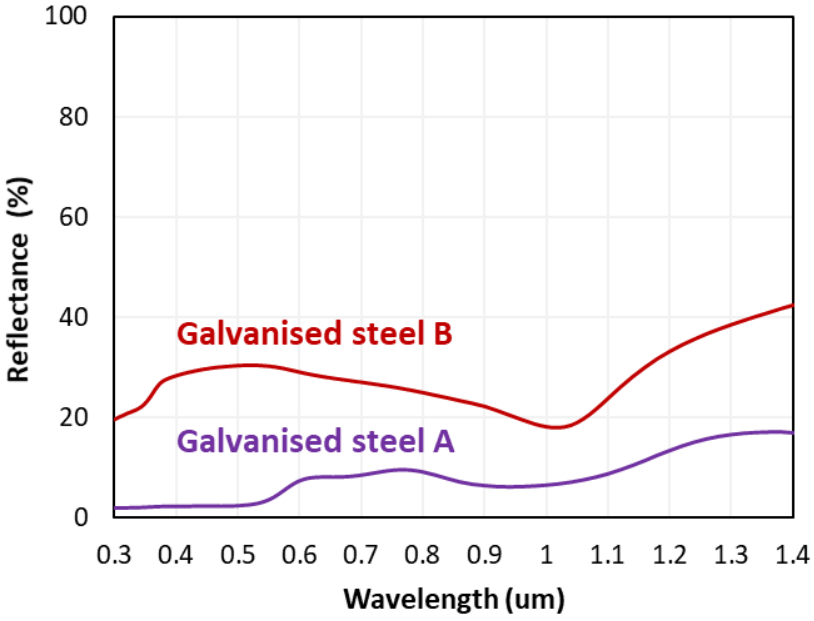
- Direct and diffuse light on rear is different to the front.
- Direct light reflected more onto bottom of the module, depends on the time of day.
- Torque-tube shading.



More complications of rear illumination

- Solar spectrum changes throughout day & year.
- Solar spectrum differs for direct and diffuse light.
- Reflectance of ground and torque-tube depend on wavelength.

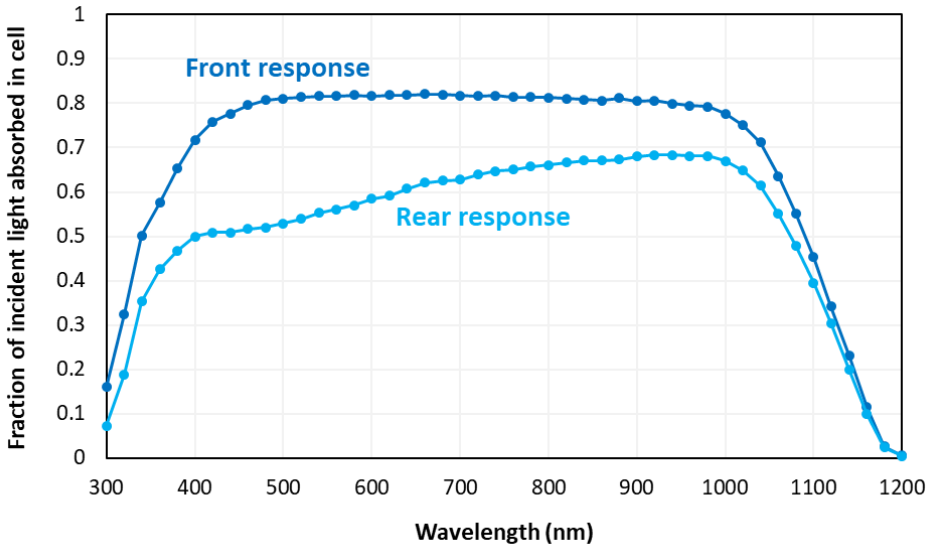




Data from NASA databases: https://speclib.jpl.nasa.gov/.

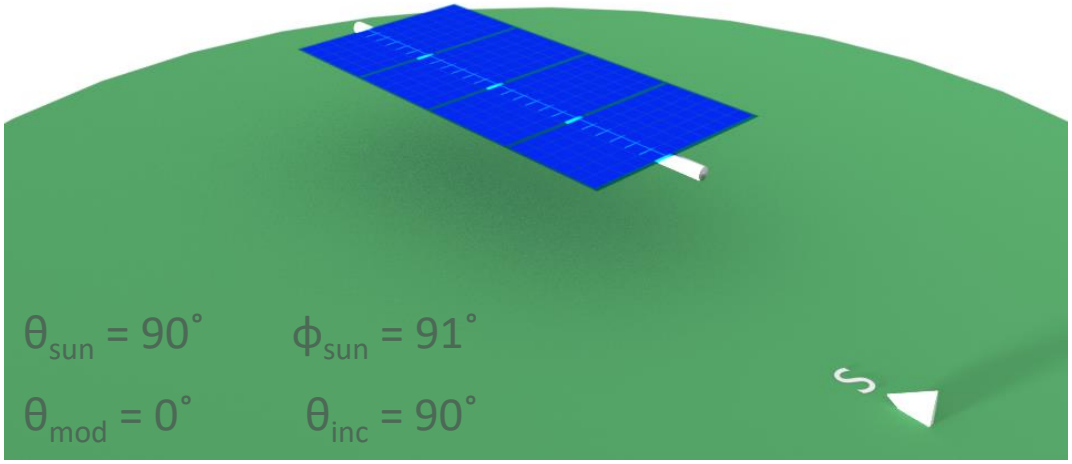
More complications of rear illumination

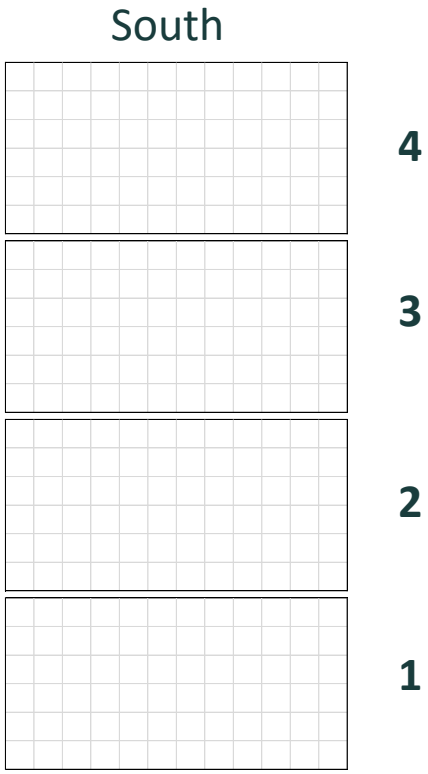
- Solar spectrum changes throughout day & year.
- Solar spectrum differs for direct and diffuse light.
- Reflectance of ground and torque-tube depend on wavelength.
- Module's response depends on wavelength and incident angle.
- Module's rear response differs to front response.

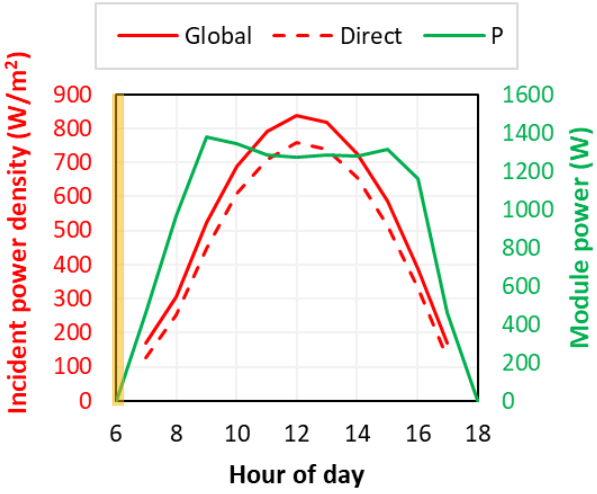


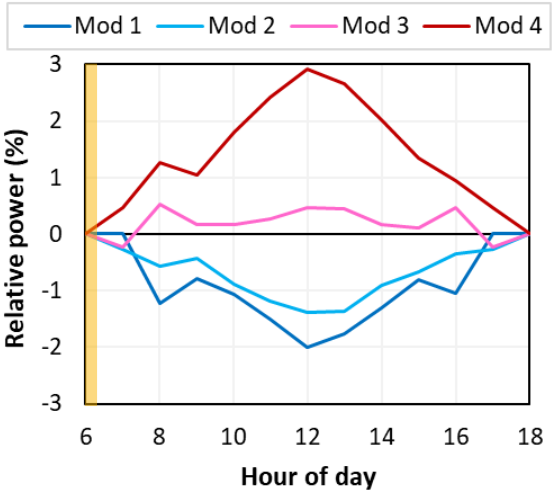
As simulated by PV Lighthouse for contemporary bifacial module under normal incidence.

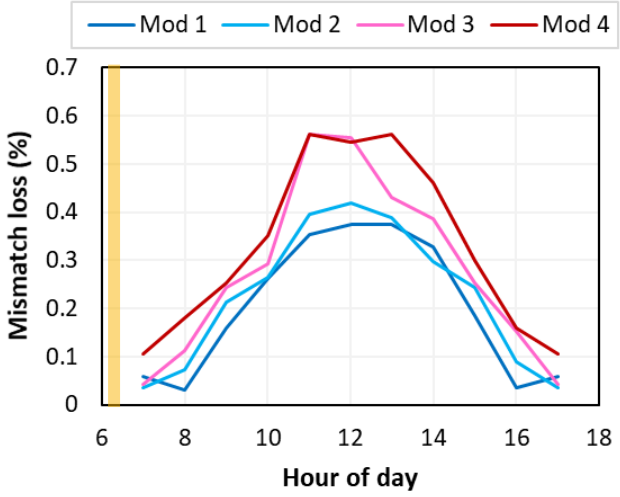
Mismatch within a module











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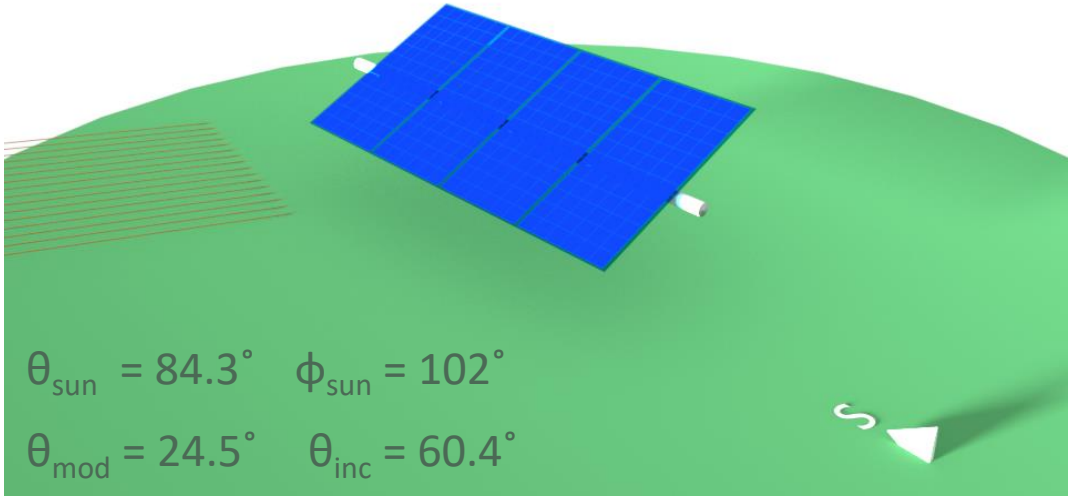

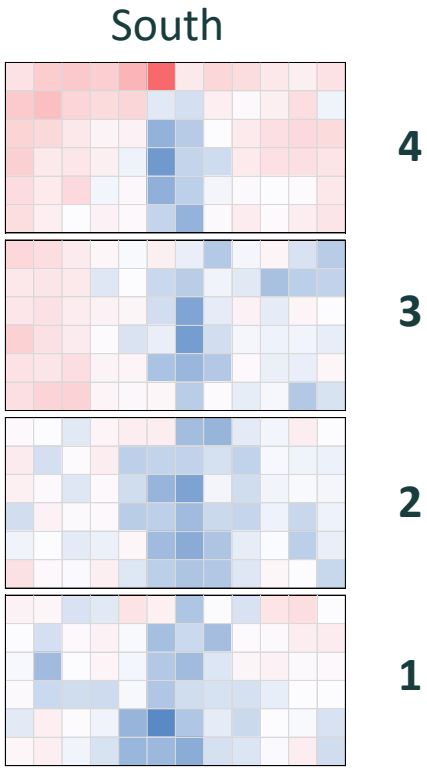

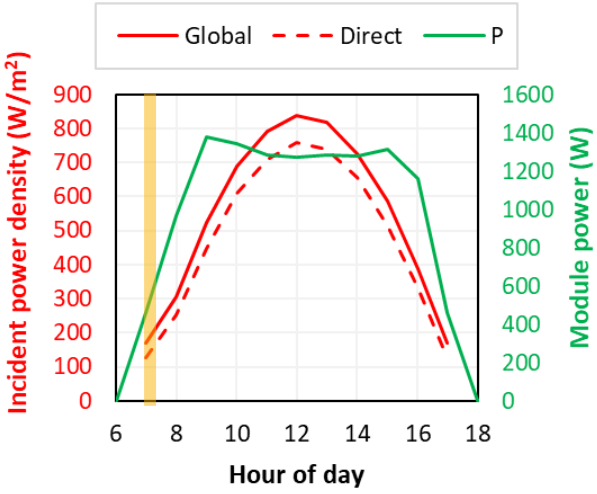

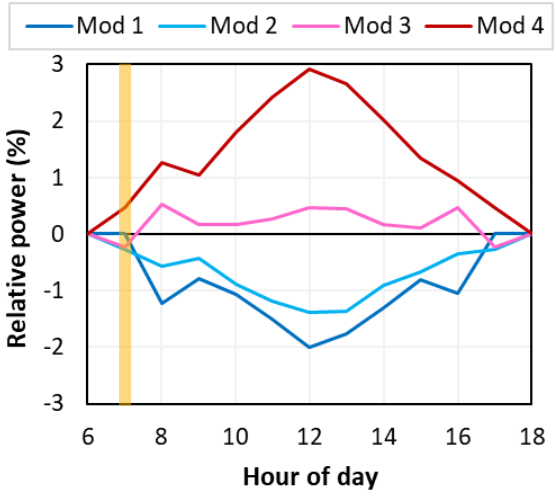

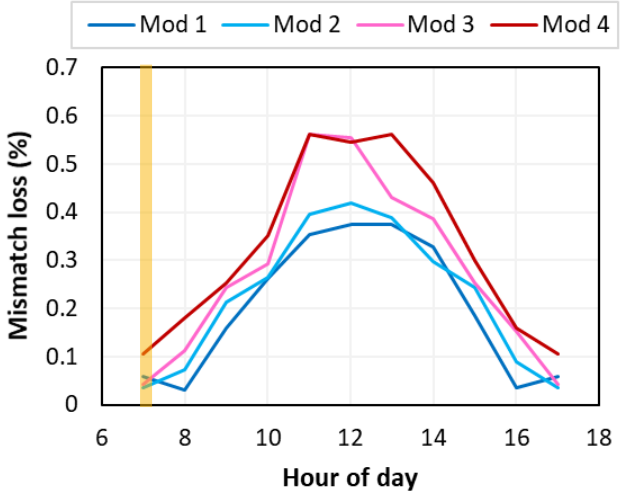

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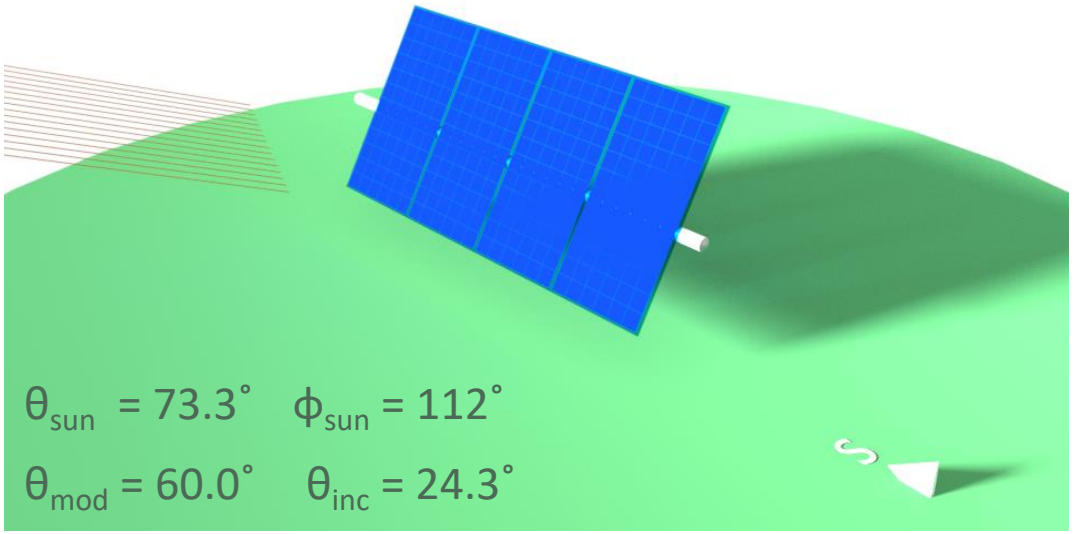

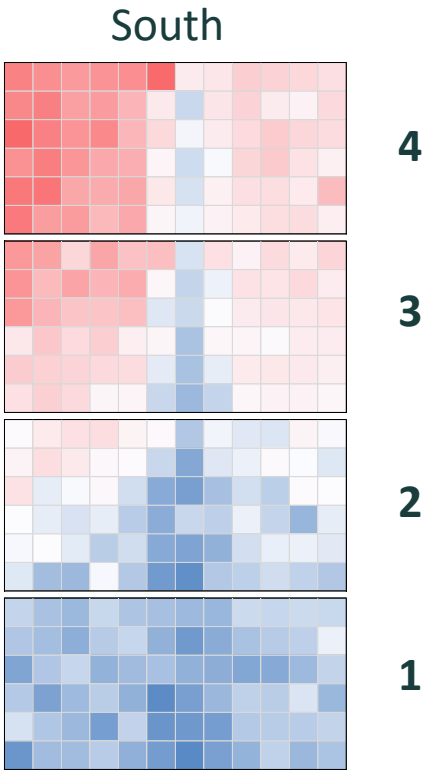

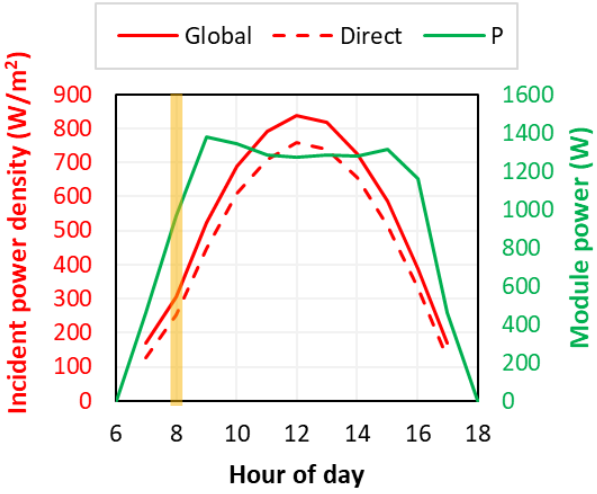

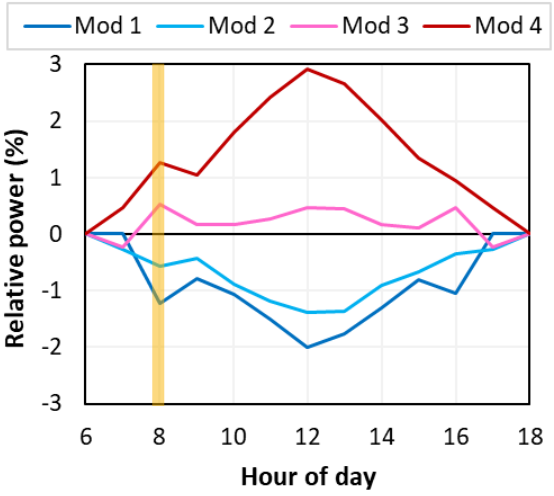

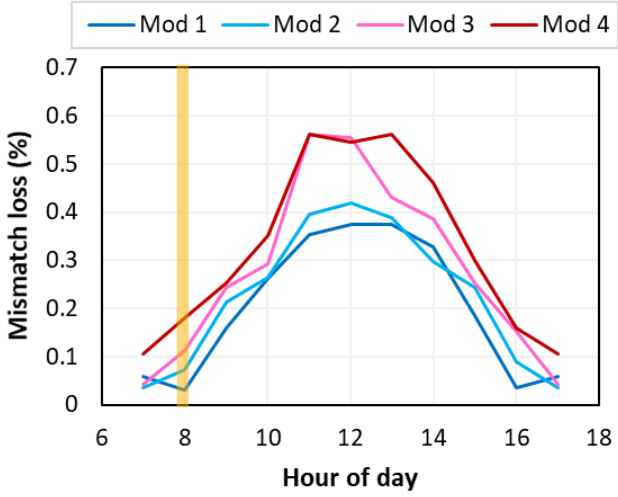

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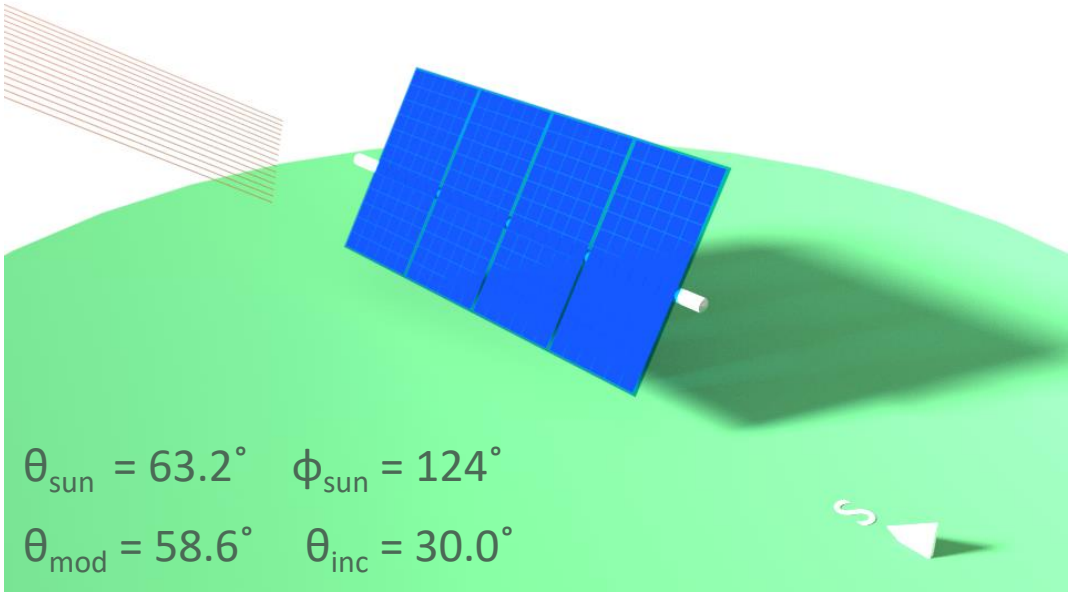

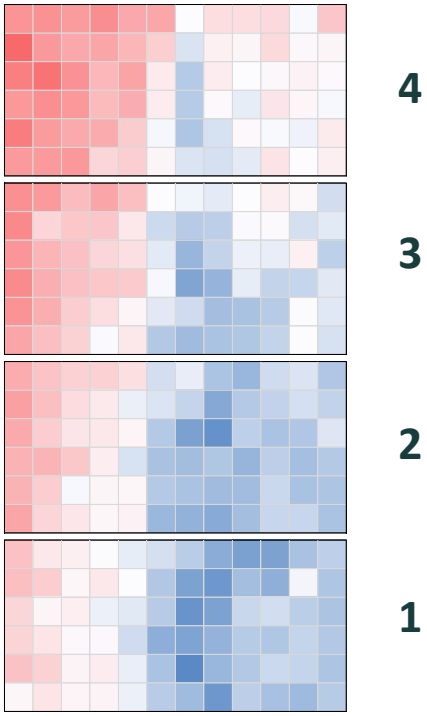

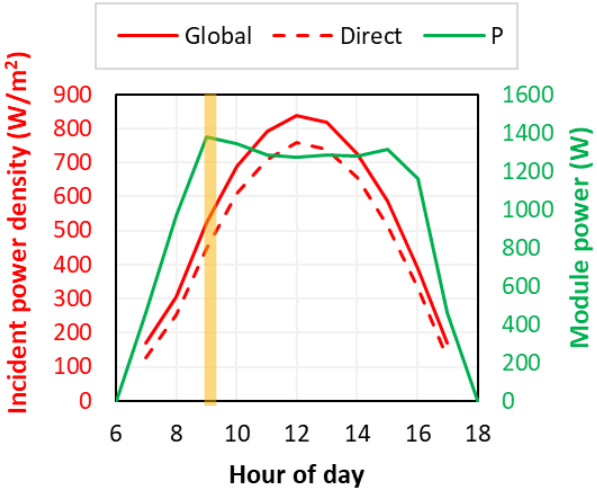

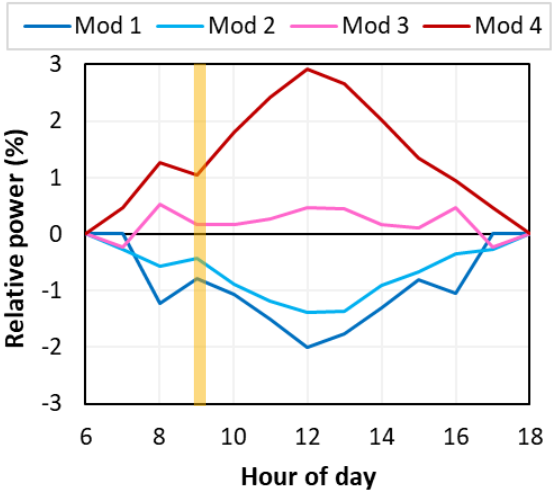

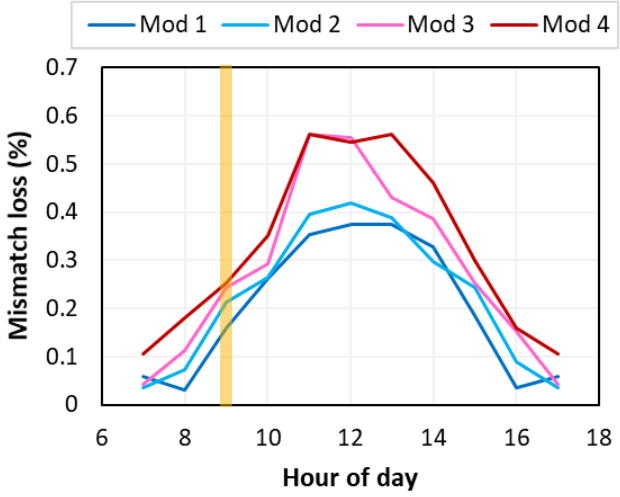

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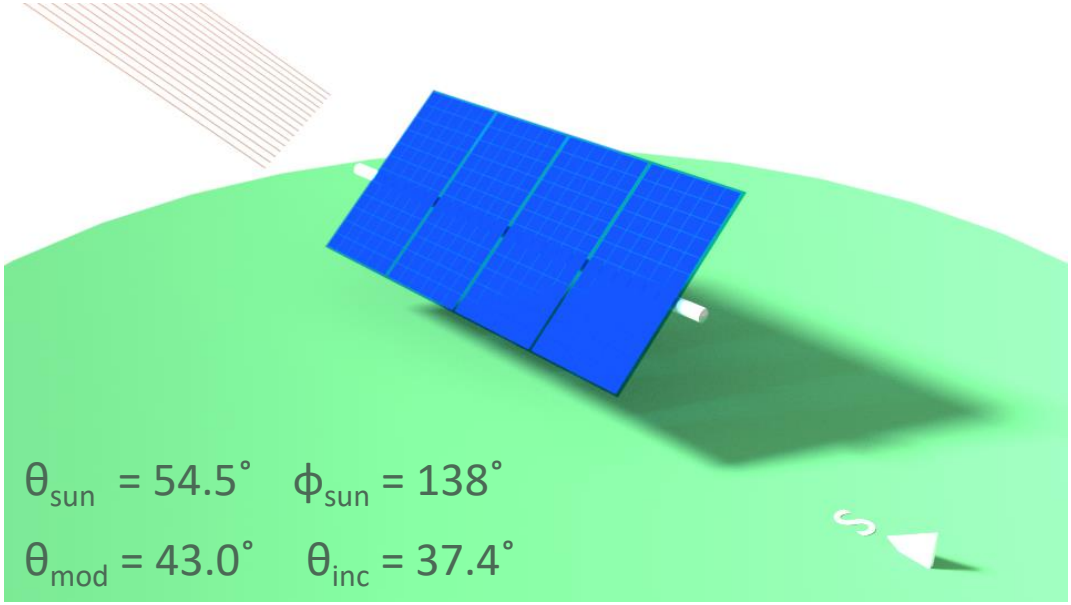
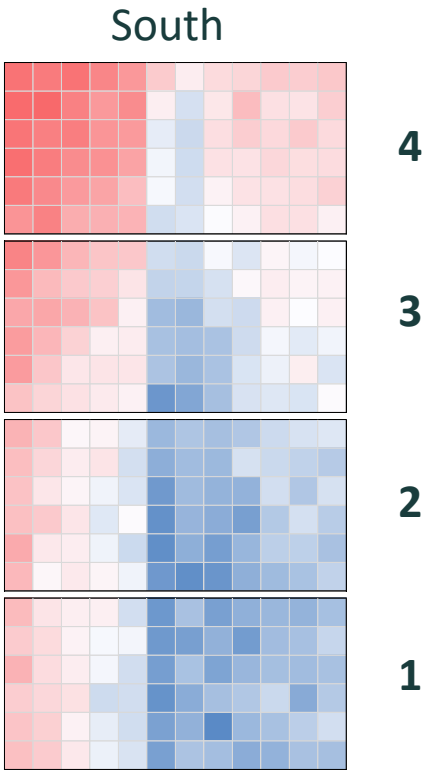
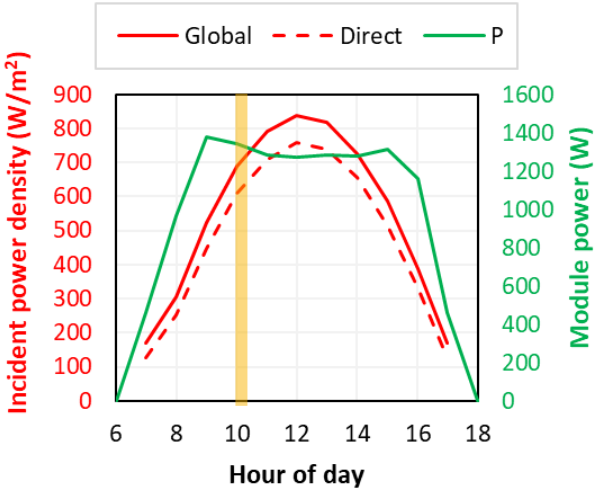
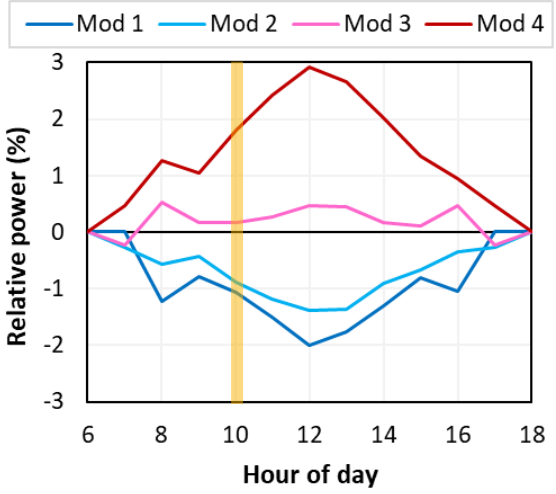
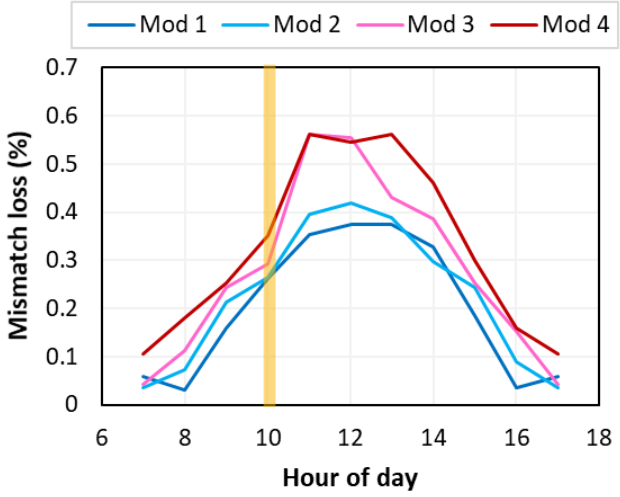


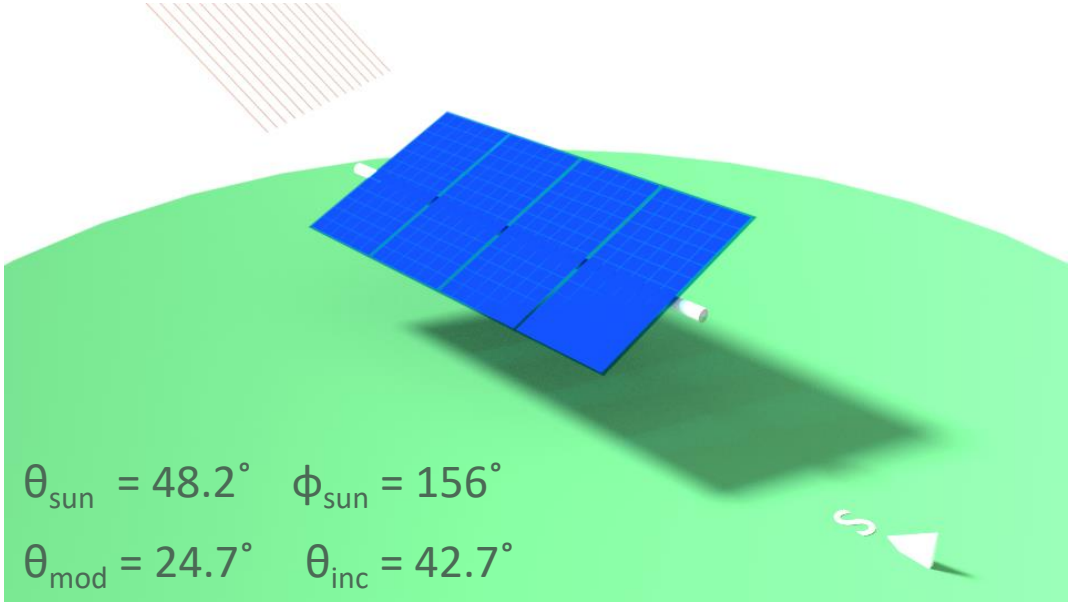


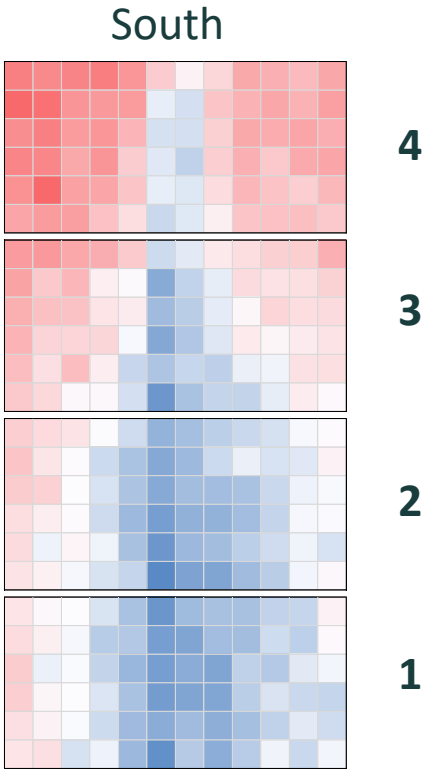


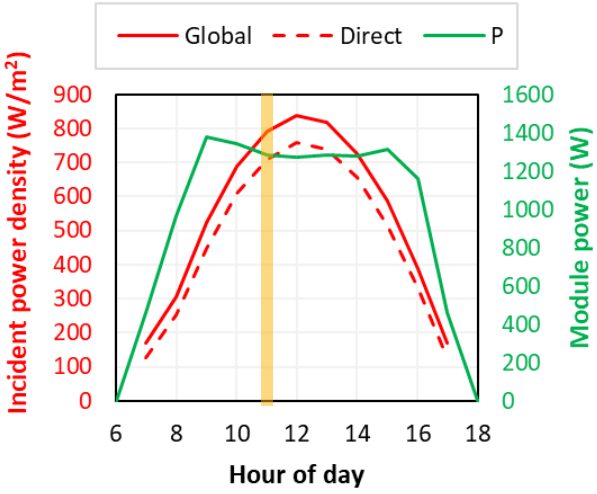


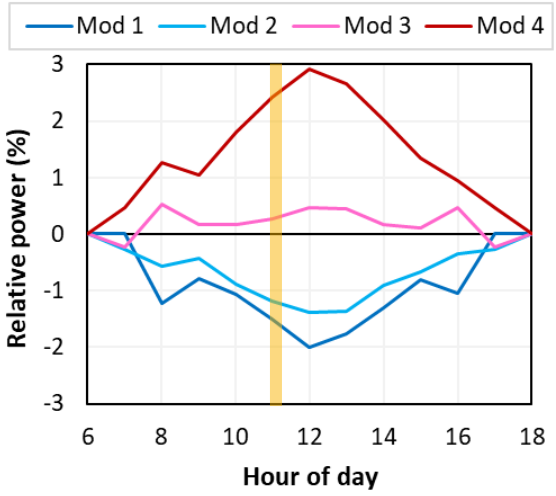


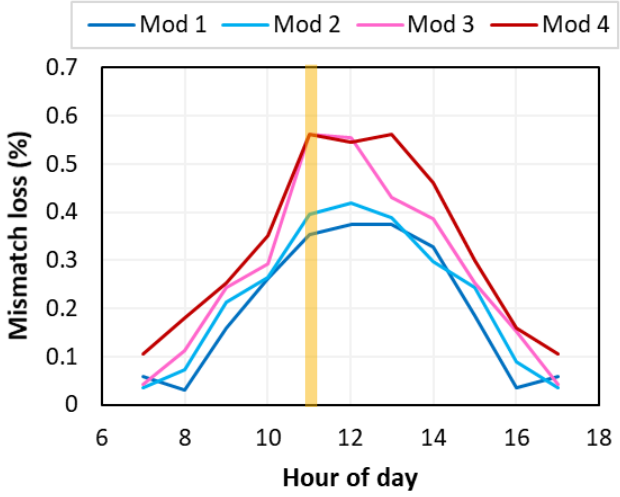
Mismatch within a module











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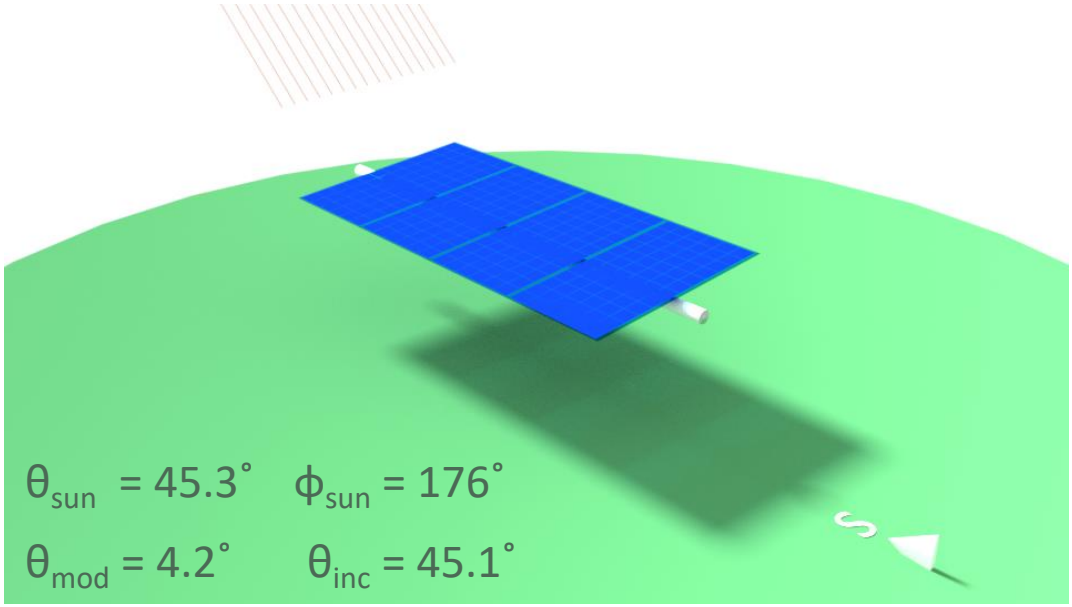
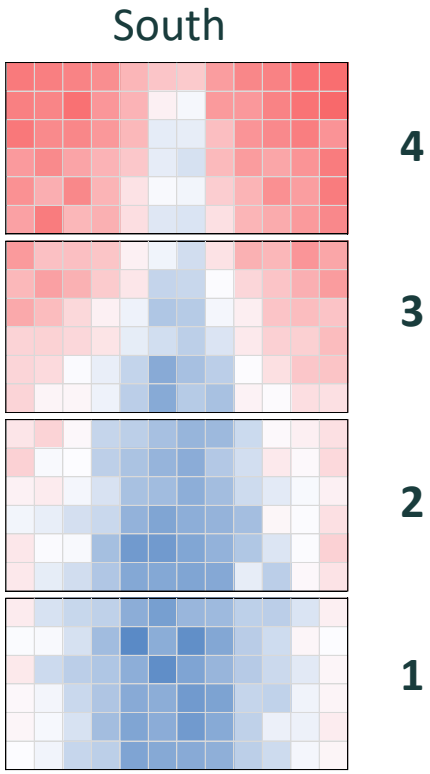
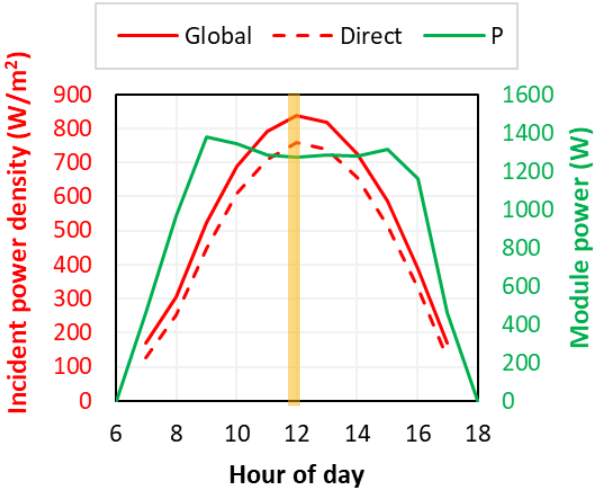
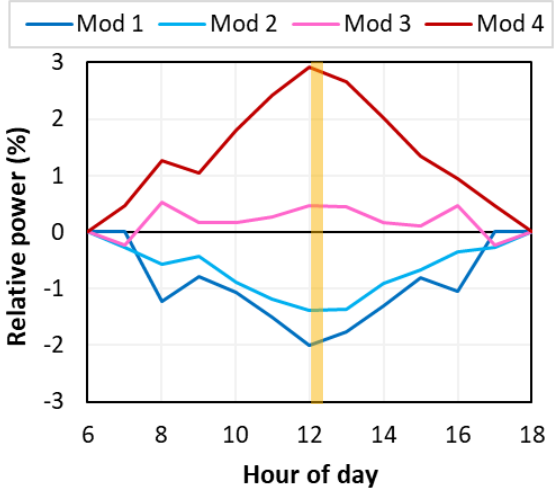
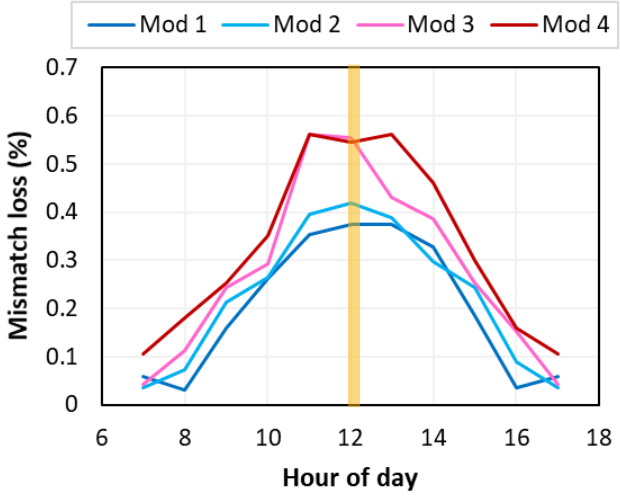


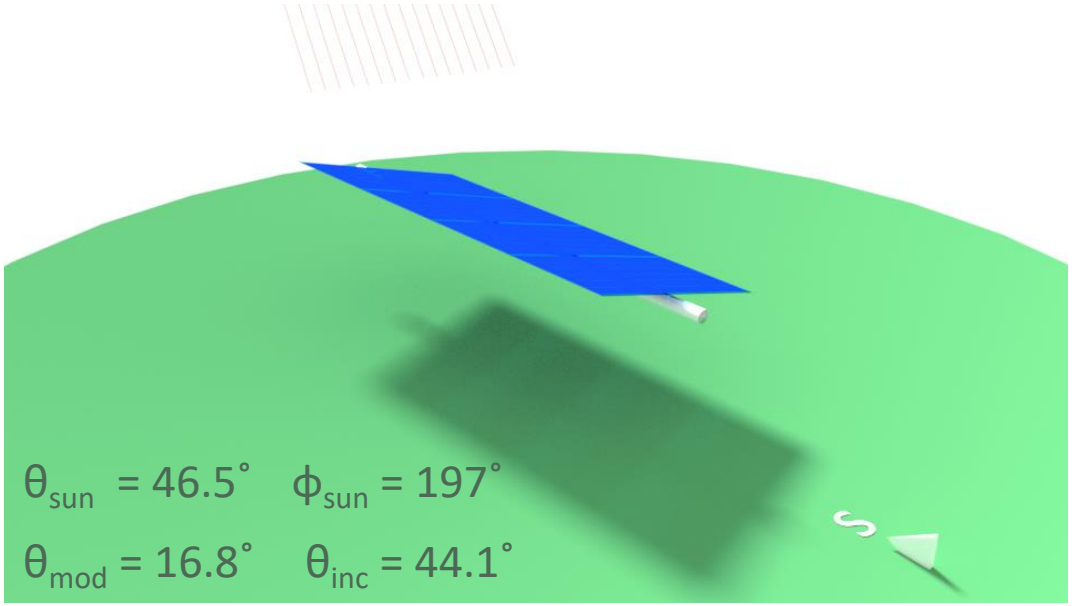


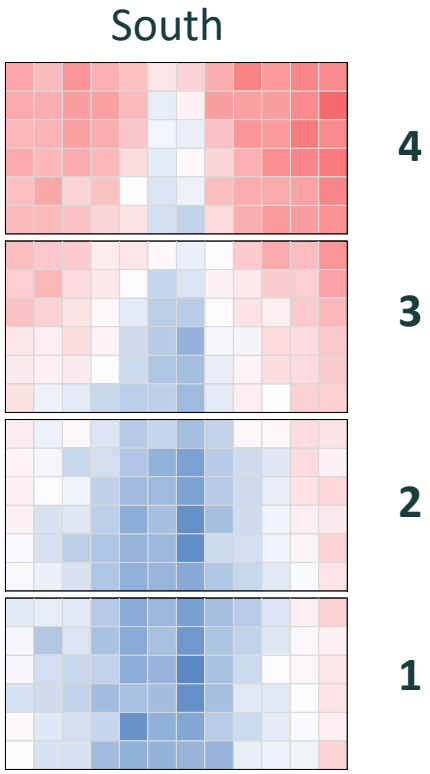


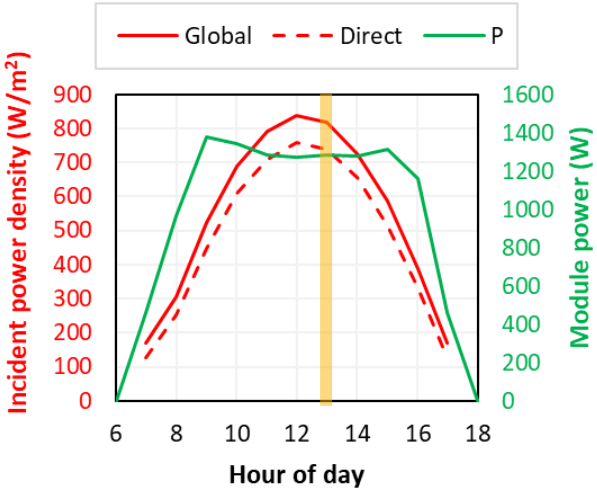


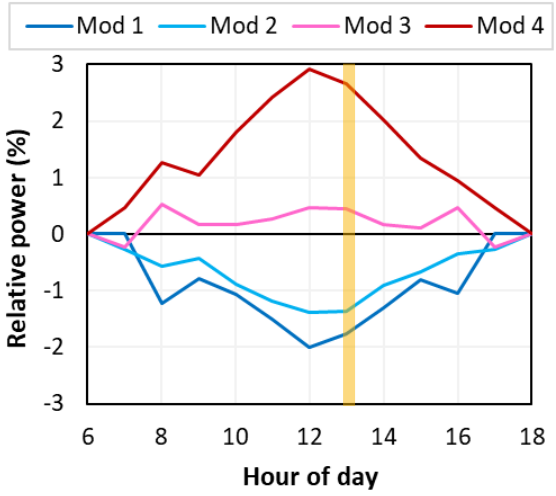


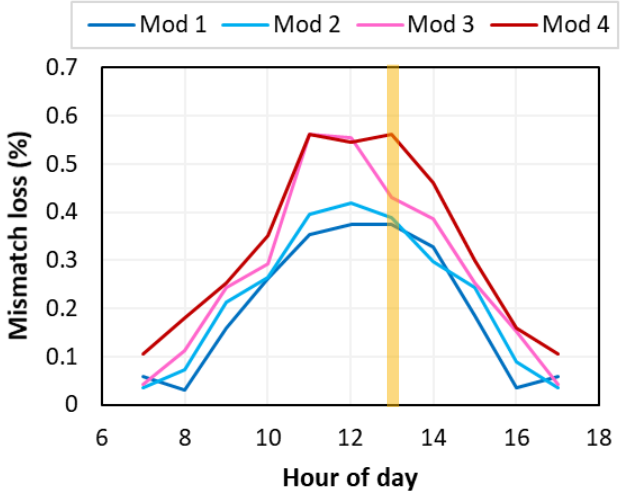
Mismatch within a module



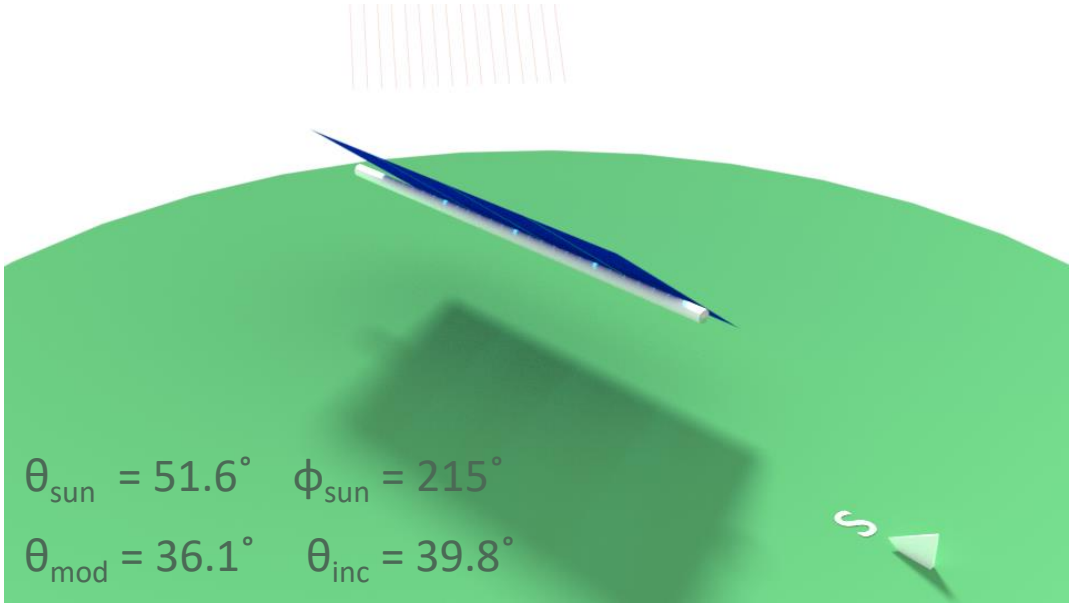


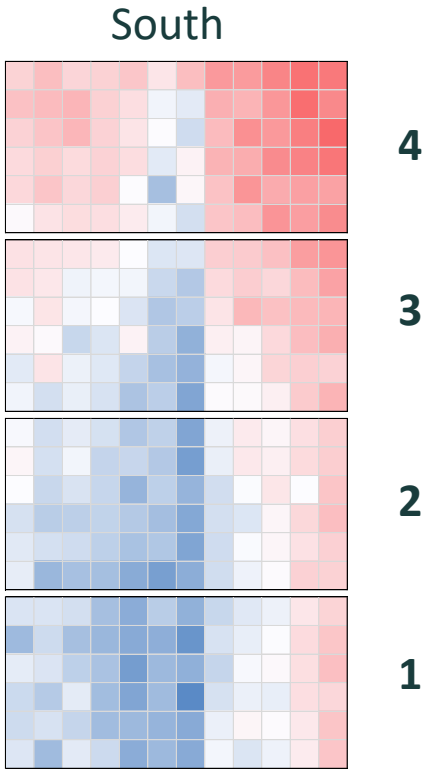


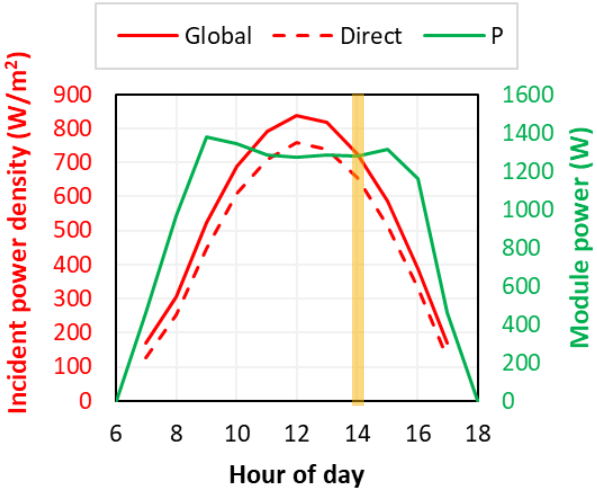


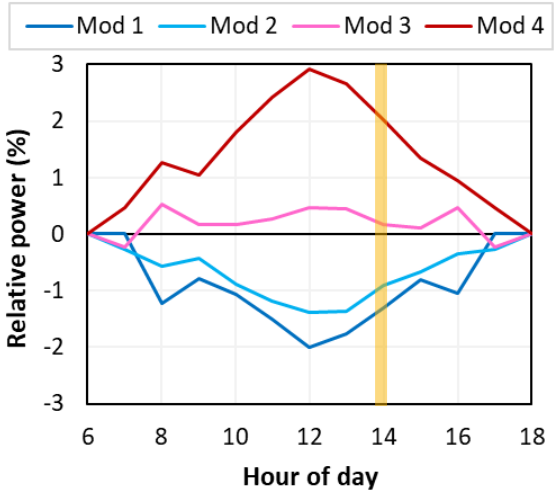


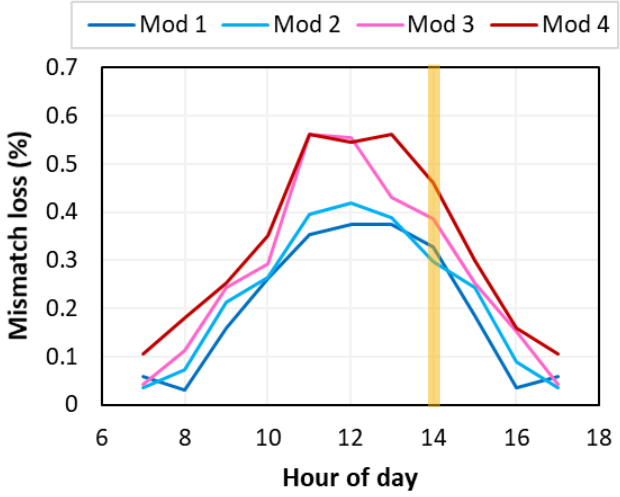
Mismatch within a module











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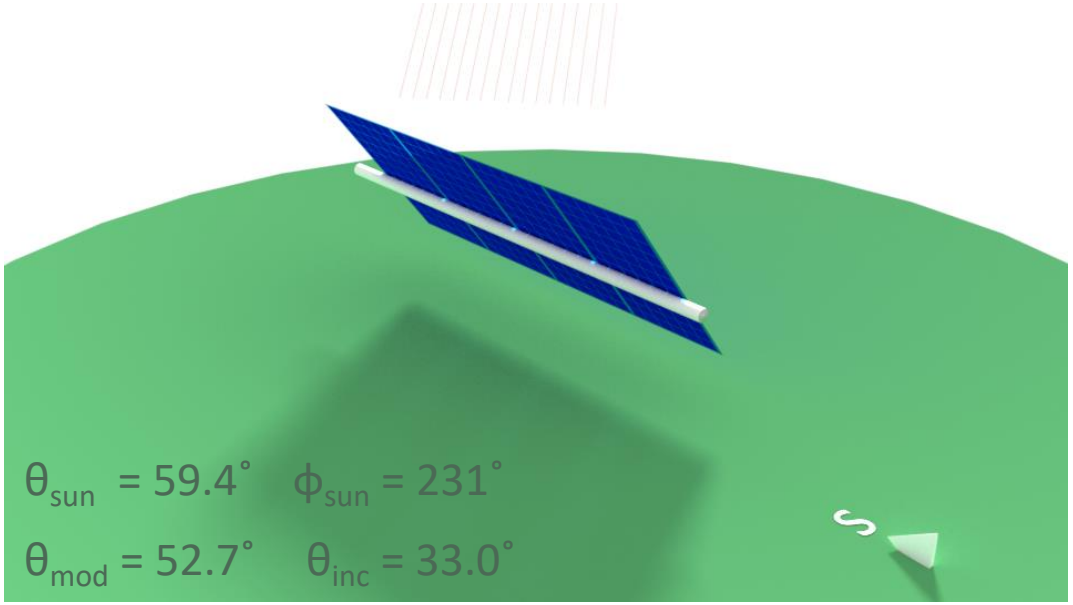

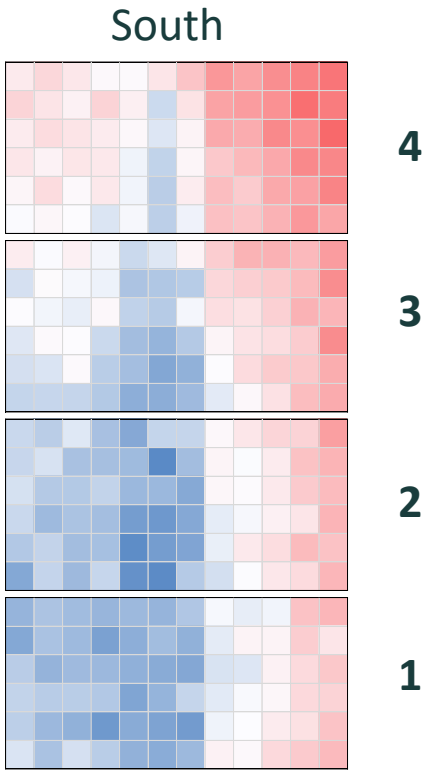

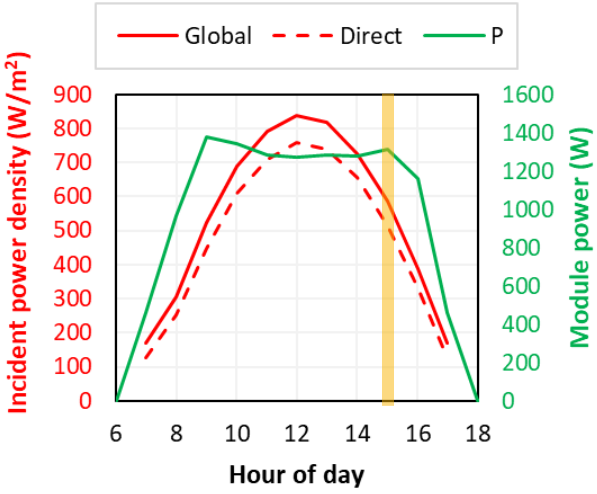

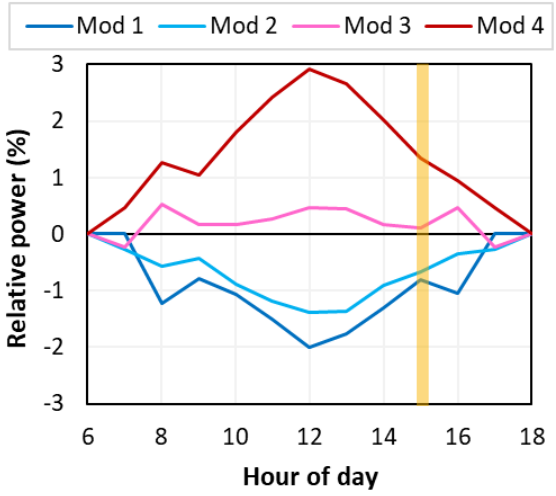

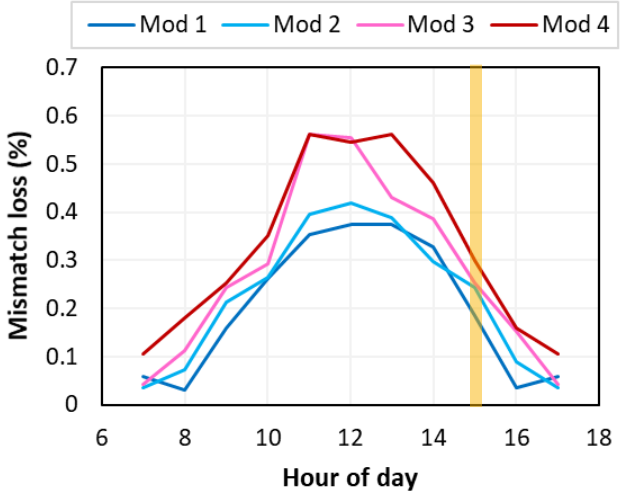

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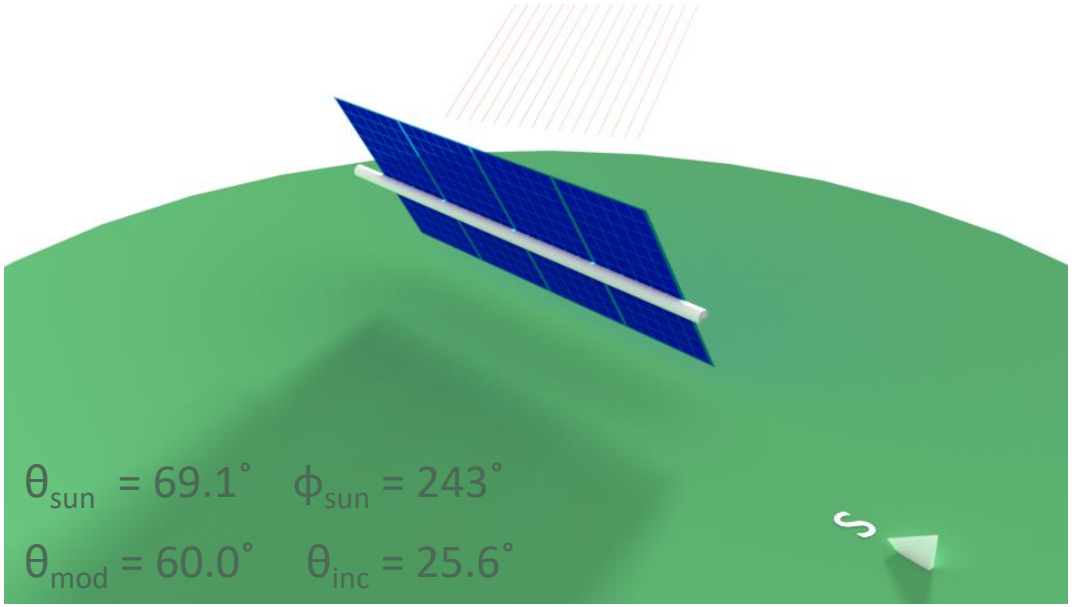
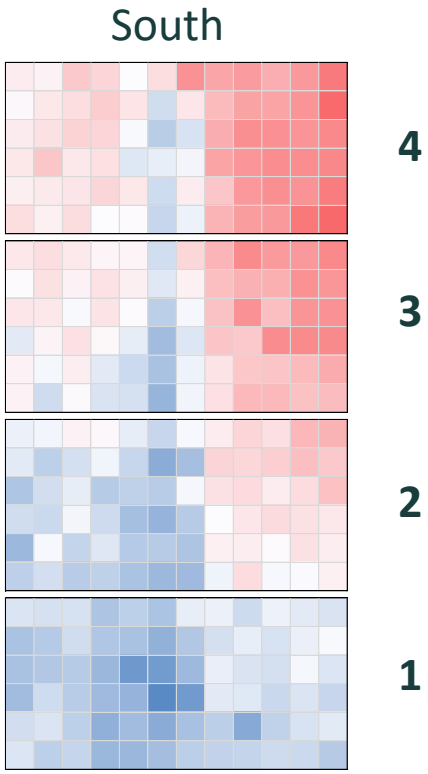
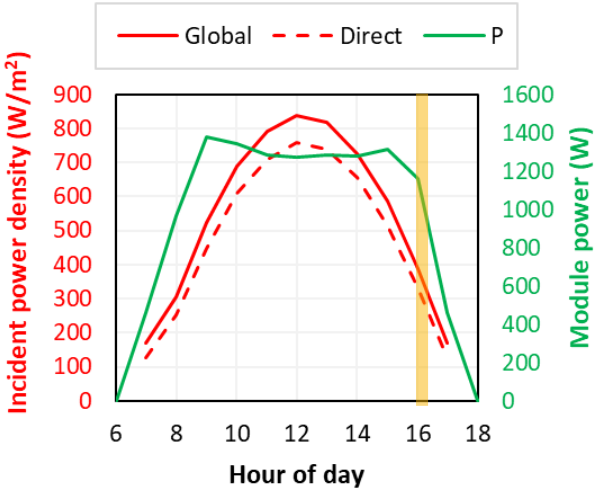
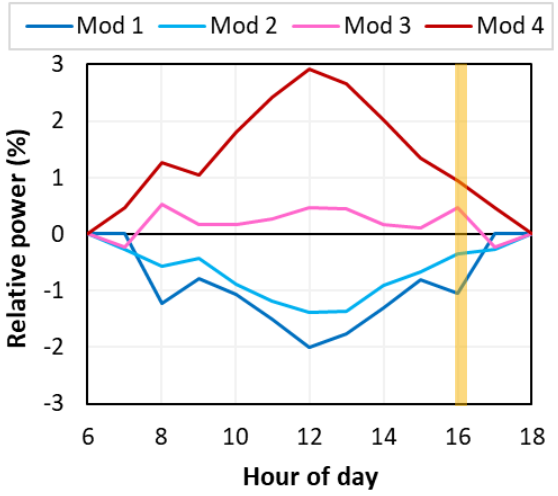
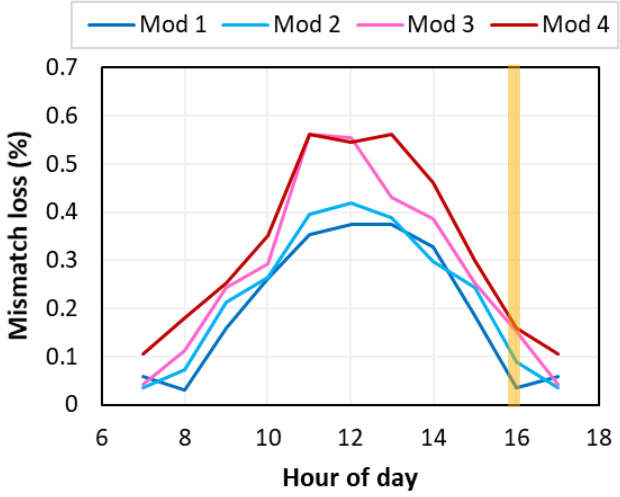


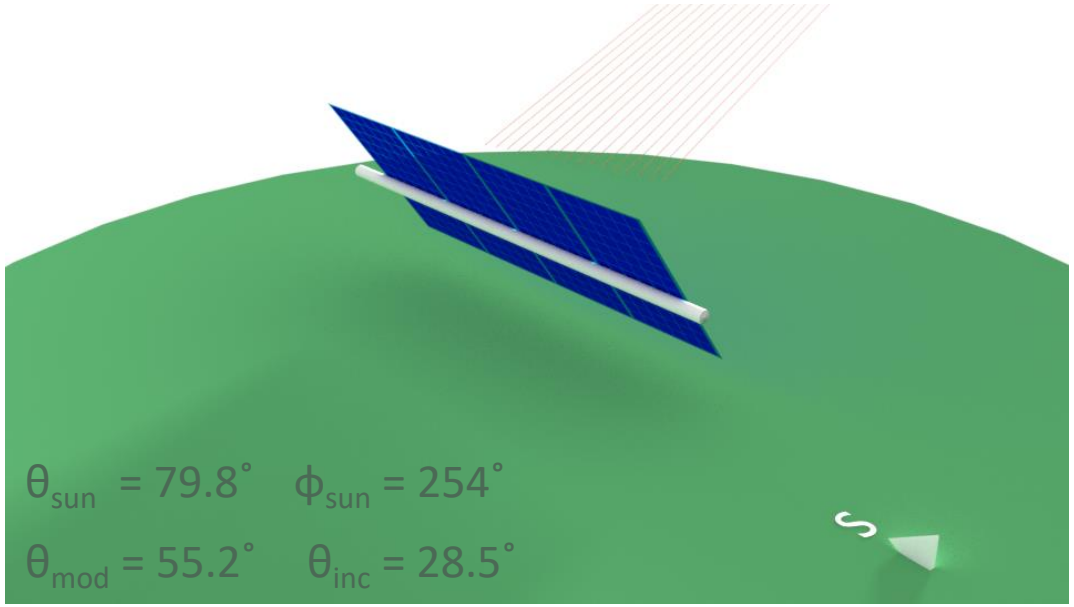


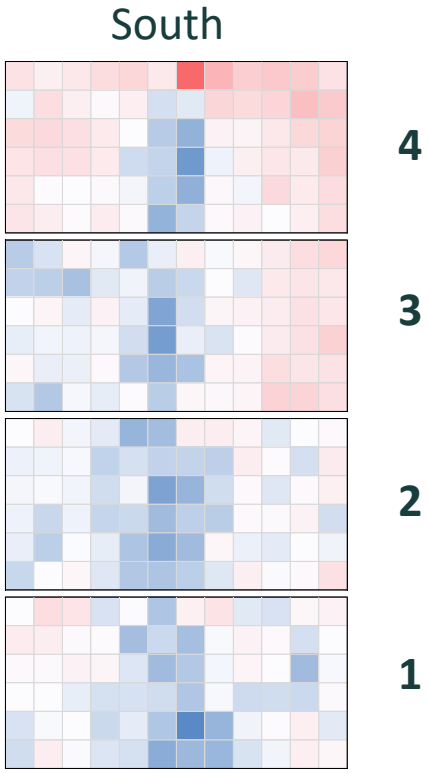


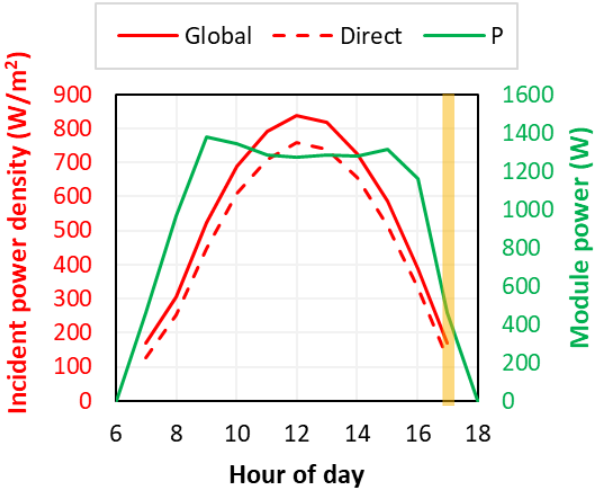


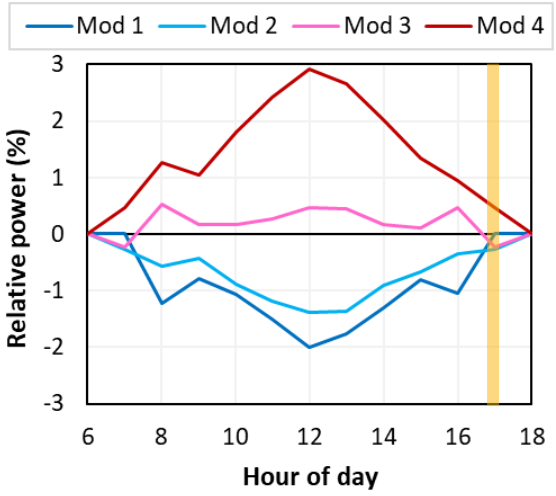


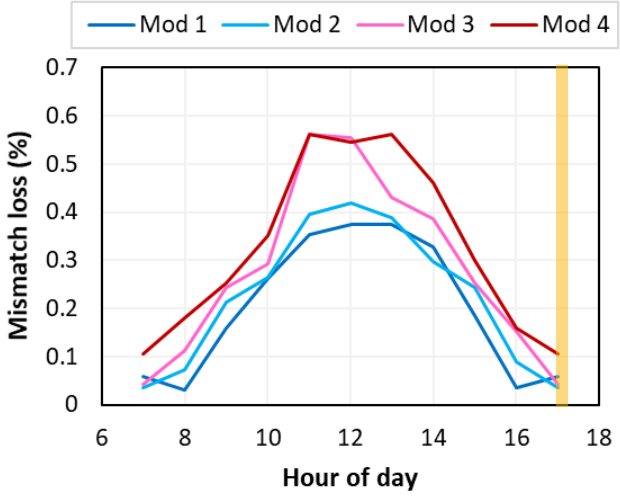
Mismatch within a module



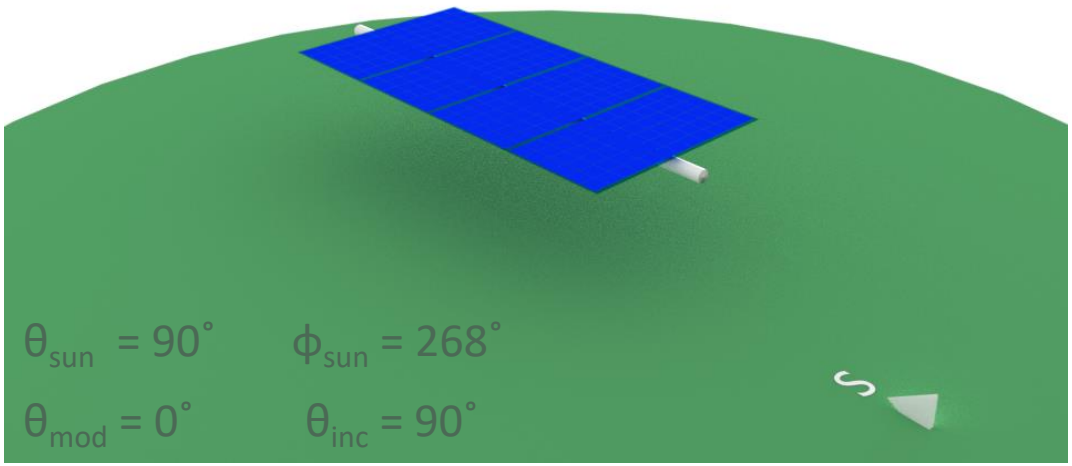


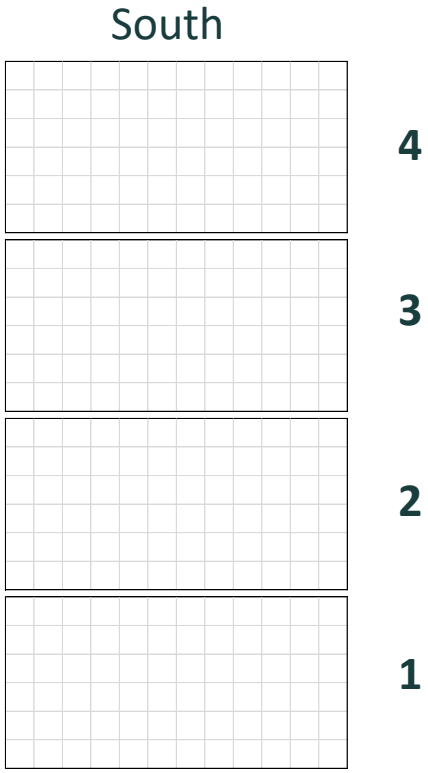


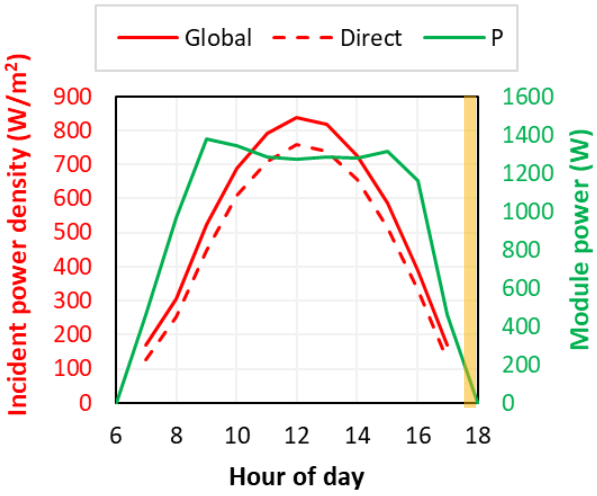


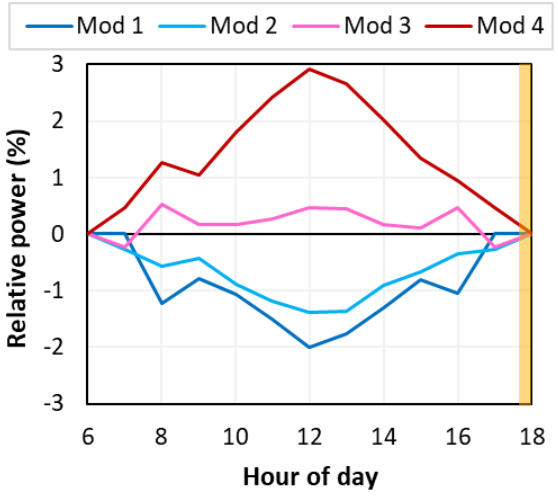


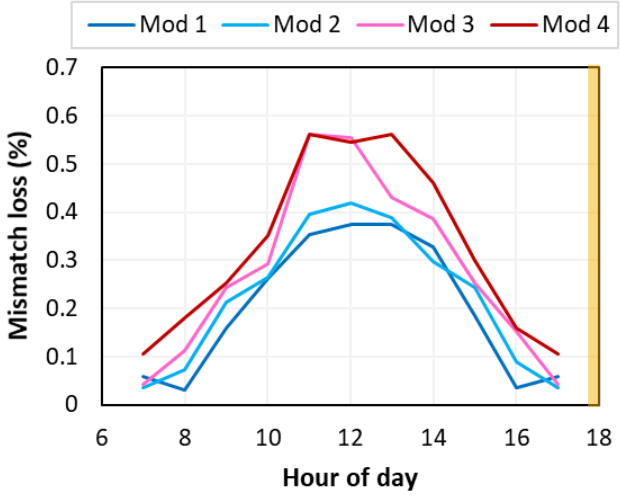
Mismatch within a module



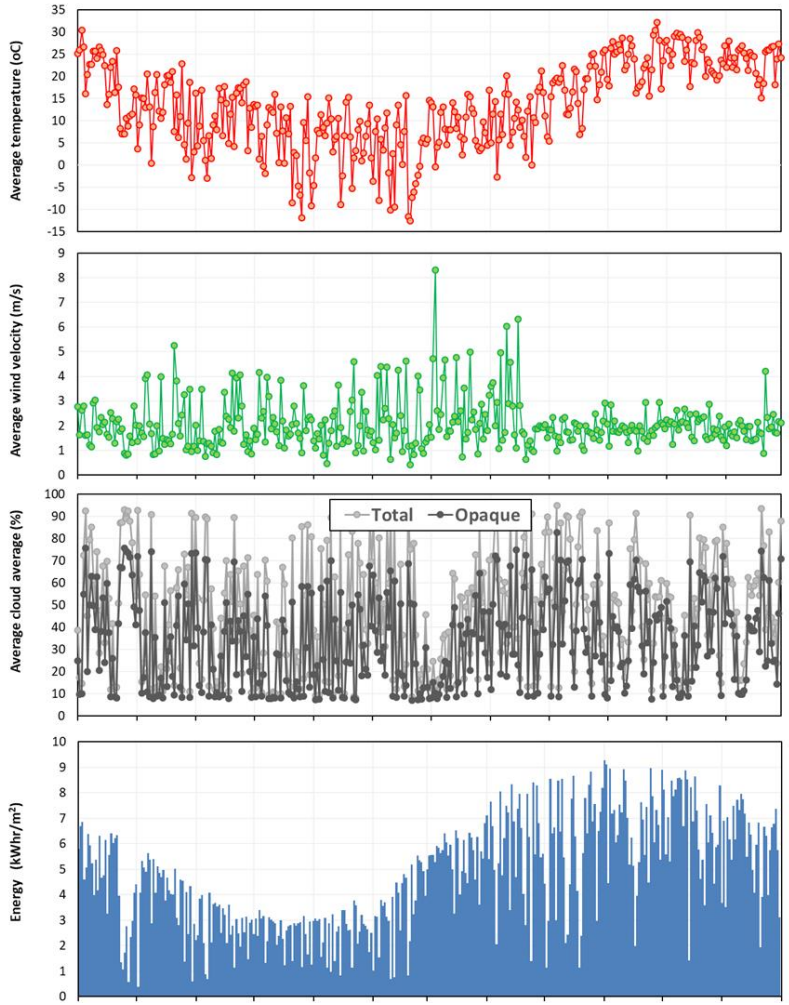








12-months at NREL, Colorado

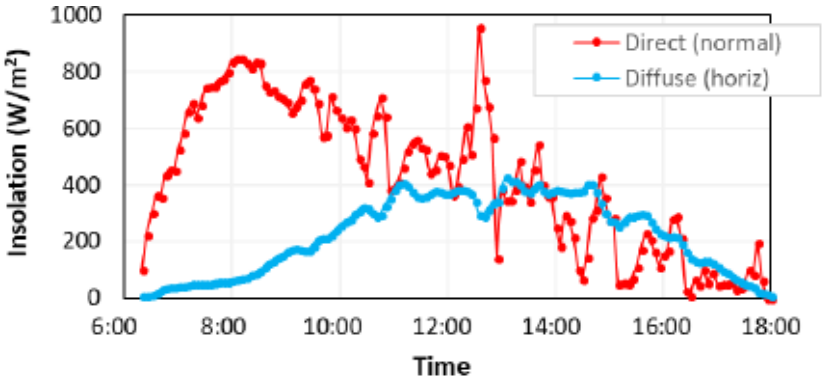


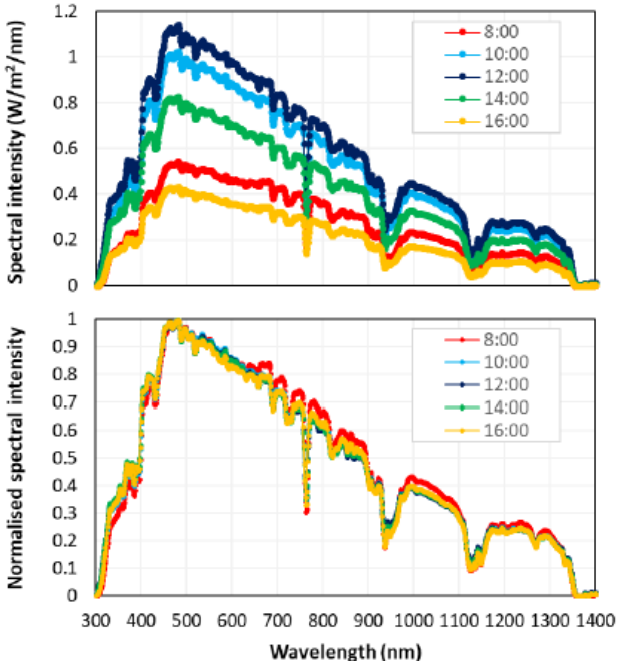
1-Sep-2017 31-Aug-2018

- Ambient temperature.
- Wind velocity.
- Cloud fraction.
- Incident global intensity.

Data from NREL databases

12-months at NREL, Colorado





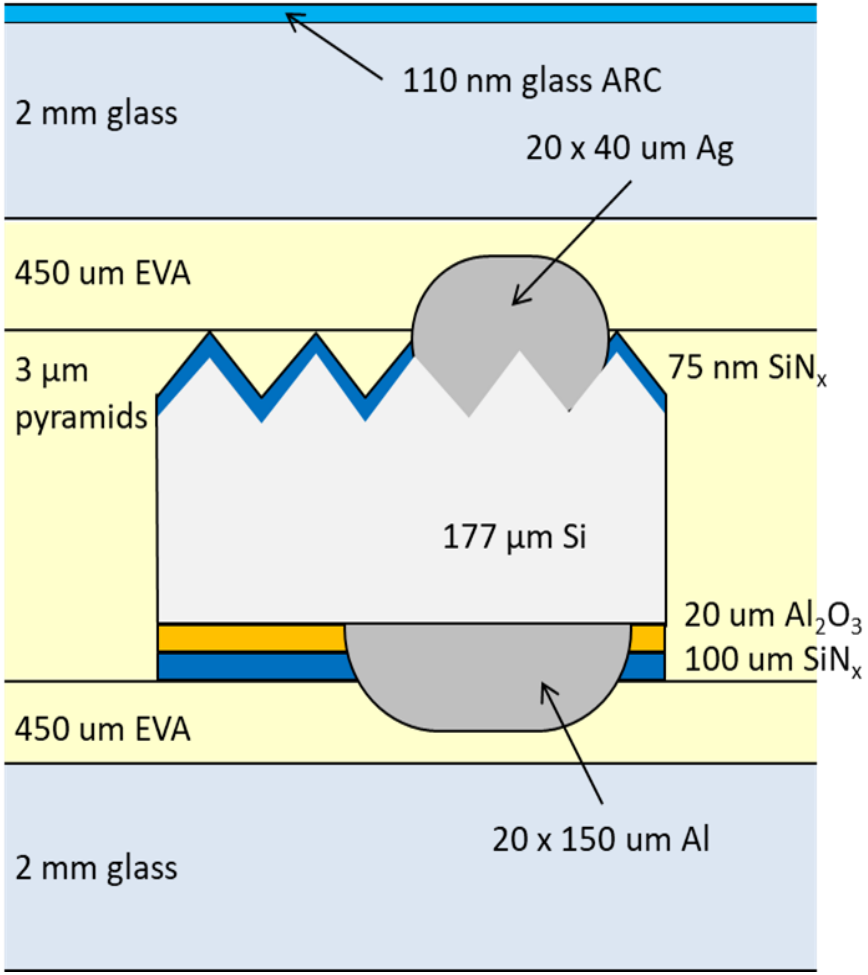
Data from NREL databases for 14-Mar-2018.

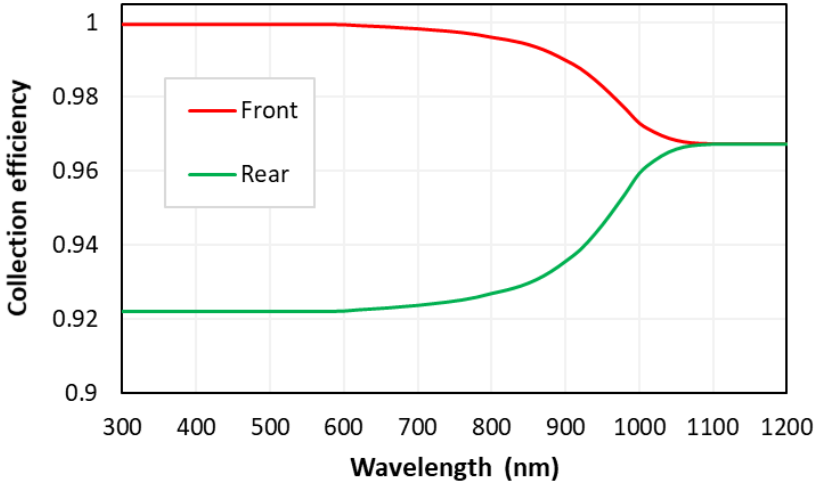
- Integrated direct intensity
- Integrated diffuse intensity

- Global spectra
- Direct spectra

→ Diffuse spectra

Modern 72-cell bifacial module



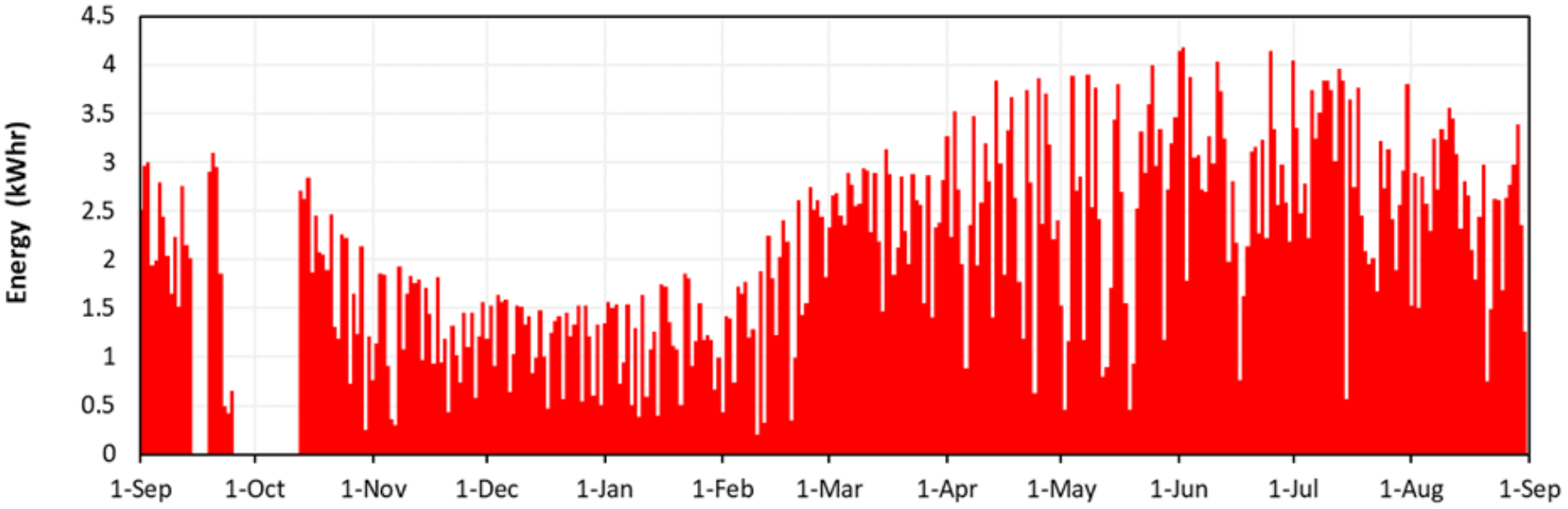


IV parameters at STC under uniform illumination.

	I_{SC} (A)	V_{OC} (V)	P_{MP} (W)
Front illumination			
Datasheet	9.58	47.5	360
Simulated	9.504	47.54	358.9
Rear illumination			
Datasheet	7.33	47.2	271
Simulated	7.330	47.06	276.8

Solve annual yield

- 20 million rays per incident angle.
- 4400 solutions per year (hourly in daylight hours).
- ~45 mins to solve the annual yield per system configuration (ray tracing + temperature solving + SPICE solving).
- Ways to reduce solutions to <5 mins have been identified.



Example: 1-high central module, sunny day

(a) 8 AM

0.3%	0.6%	0.2%	0.5%	0.8%	0.5%
0.2%	0.4%	-0.1%	0.2%	0.2%	-0.2%
0.6%	0.2%	0.4%	0.5%	0.5%	0.4%
0.0%	-0.1%	0.0%	0.0%	0.3%	-0.1%
0.1%	0.3%	0.2%	-0.4%	0.3%	0.3%
0.2%	-0.1%	0.2%	-0.4%	-0.2%	0.9%
-0.6%	-0.2%	-0.4%	-0.5%	-0.6%	0.4%
0.0%	-0.3%	-0.2%	-0.2%	-0.6%	-0.4%
-0.5%	-0.3%	-0.1%	0.0%	-0.3%	-0.1%
0.1%	-0.2%	-0.2%	-0.3%	-0.4%	-0.2%
-0.1%	0.0%	-0.2%	-0.4%	0.0%	-0.2%
-0.2%	-0.2%	-0.2%	-0.1%	0.3%	-0.2%

(b) 10 AM

4.2%	4.0%	4.1%	4.4%	4.2%	4.6%
2.7%	2.8%	3.1%	3.1%	3.2%	2.9%
1.7%	1.6%	1.6%	1.9%	2.0%	1.5%
1.1%	1.0%	1.0%	1.1%	0.9%	1.1%
0.6%	0.3%	-0.1%	0.0%	0.1%	0.6%
-1.3%	-1.7%	-1.8%	-1.6%	-1.4%	-1.1%
-1.4%	-1.7%	-1.5%	-1.3%	-1.7%	-0.9%
-2.1%	-2.3%	-2.5%	-2.4%	-1.7%	-2.0%
-1.2%	-1.4%	-1.4%	-1.9%	-1.6%	-1.7%
-1.2%	-1.5%	-1.9%	-1.3%	-1.5%	-1.5%
-1.0%	-0.9%	-1.2%	-1.4%	-1.1%	-1.3%
-0.8%	-1.2%	-1.0%	-0.9%	-1.1%	-0.8%

(c) 12 PM

2.7%	2.3%	2.6%	2.5%	3.3%	2.2%
1.6%	1.4%	1.3%	1.6%	1.7%	1.2%
0.8%	1.2%	0.7%	0.5%	0.8%	0.7%
-0.1%	-0.6%	-0.7%	-0.5%	-0.6%	0.1%
-1.8%	-2.1%	-1.9%	-1.5%	-1.6%	-1.9%
-2.1%	-3.2%	-2.2%	-2.4%	-1.8%	-1.7%
-2.3%	-1.8%	-1.8%	-1.9%	-1.9%	-1.1%
-2.3%	-2.2%	-2.1%	-2.1%	-2.1%	-2.4%
-1.0%	-0.5%	-0.3%	-0.6%	-0.6%	-0.6%
0.7%	0.5%	1.4%	0.3%	0.3%	0.4%
1.3%	1.7%	1.6%	1.6%	1.2%	0.9%
2.1%	2.1%	1.9%	2.5%	2.3%	2.9%

(d) 2 PM

-0.7%	-0.5%	-0.2%	-0.5%	-0.7%	-0.6%
-0.9%	-0.3%	-0.6%	-0.5%	-0.6%	-0.8%
-1.1%	-1.3%	-0.4%	-1.2%	-1.0%	-0.8%
-1.5%	-1.6%	-1.2%	-1.6%	-1.6%	-1.6%
-2.4%	-2.0%	-2.6%	-2.0%	-2.2%	-2.1%
-1.2%	-1.4%	-1.3%	-1.3%	-1.0%	-1.1%
-2.3%	-2.6%	-2.4%	-2.4%	-2.6%	-1.7%
0.1%	-0.2%	-0.3%	-0.3%	0.1%	0.4%
0.8%	0.5%	1.3%	0.8%	1.0%	0.9%
1.3%	1.7%	1.3%	1.8%	2.0%	2.2%
2.5%	2.2%	2.4%	2.8%	2.7%	2.8%
4.2%	3.7%	4.1%	4.3%	4.5%	4.5%

(e) 4 PM

-0.5%	-0.7%	-0.2%	-0.4%	-0.3%	-0.7%
-0.4%	-0.6%	-0.9%	-0.3%	-0.4%	-0.6%
-0.7%	-0.4%	-0.2%	-0.4%	-0.3%	-0.8%
-0.3%	-0.9%	-0.5%	-0.4%	-0.8%	-0.4%
-0.7%	-1.2%	-0.7%	-0.8%	-1.2%	-0.8%
-0.2%	-0.7%	-0.5%	-0.7%	-0.5%	0.1%
-0.2%	-0.3%	-0.2%	0.1%	-0.5%	0.6%
0.6%	0.0%	0.0%	0.5%	0.3%	0.3%
0.6%	0.2%	0.0%	0.2%	0.6%	0.5%
0.3%	1.1%	0.7%	0.7%	0.7%	0.9%
1.1%	1.1%	0.9%	0.7%	0.7%	1.0%
1.4%	1.1%	1.4%	1.3%	0.9%	0.9%

Example: 1-high central module, cloudy day

(a) 8 AM

1.0%	1.6%	2.0%	1.3%	1.3%	1.8%
0.6%	0.8%	1.2%	1.1%	1.4%	0.9%
0.8%	0.7%	0.4%	-0.2%	0.4%	0.5%
0.0%	0.2%	0.1%	-0.1%	0.6%	0.3%
-1.5%	-1.1%	-0.7%	-0.6%	-0.6%	-1.0%
-2.4%	-2.9%	-1.9%	-2.4%	-3.7%	-2.6%
-2.6%	-3.0%	-2.5%	-3.2%	-3.4%	-3.0%
-0.8%	-0.9%	-1.0%	-1.1%	-1.1%	-0.7%
0.1%	0.0%	0.0%	0.4%	0.4%	1.2%
1.4%	0.7%	1.3%	1.1%	0.5%	0.8%
1.8%	1.0%	1.7%	1.0%	2.0%	1.2%
1.3%	2.0%	1.7%	1.1%	1.4%	1.9%

(b) 10 AM

1.2%	1.6%	1.1%	1.9%	1.0%	1.5%
1.1%	1.5%	1.6%	1.3%	0.7%	1.2%
0.5%	1.1%	1.1%	0.5%	0.8%	0.8%
0.2%	0.0%	0.4%	0.1%	0.9%	0.6%
-1.0%	-1.5%	-0.8%	-1.0%	-1.2%	-1.0%
-2.0%	-3.0%	-2.7%	-3.0%	-2.0%	-2.5%
-2.4%	-3.1%	-3.1%	-2.7%	-2.2%	-3.4%
-0.9%	-0.6%	-1.0%	-1.1%	-0.8%	-1.1%
0.5%	0.1%	0.3%	0.6%	-0.2%	0.8%
0.0%	0.7%	1.3%	0.7%	0.4%	0.6%
1.1%	1.7%	0.9%	1.6%	1.2%	0.5%
1.9%	1.2%	1.6%	1.1%	1.0%	1.6%

(c) 12 PM

1.4%	1.2%	1.8%	1.5%	1.4%	1.1%
1.3%	1.0%	1.1%	0.6%	1.4%	0.9%
0.9%	1.1%	0.8%	0.9%	1.0%	0.2%
0.8%	0.4%	0.1%	0.2%	0.2%	-0.3%
-0.9%	-0.7%	-1.0%	-1.2%	-0.2%	-0.8%
-2.7%	-3.5%	-2.3%	-3.1%	-2.1%	-3.1%
-3.4%	-2.9%	-2.7%	-2.6%	-2.8%	-2.4%
-0.6%	-0.5%	-0.6%	-1.3%	-0.5%	-0.9%
0.4%	0.4%	0.6%	0.0%	0.4%	0.2%
0.6%	1.1%	1.1%	0.2%	0.6%	1.0%
0.8%	1.0%	0.7%	1.8%	1.6%	0.6%
0.9%	1.7%	1.4%	1.3%	1.6%	2.0%

(d) 2 PM

1.2%	1.1%	2.0%	0.9%	1.0%	1.8%
1.2%	0.5%	0.8%	0.8%	1.5%	1.5%
0.6%	0.4%	0.8%	1.4%	1.4%	1.2%
0.5%	0.6%	0.3%	0.0%	-0.5%	0.1%
-1.4%	0.0%	-1.3%	0.0%	-0.9%	-1.8%
-2.1%	-2.7%	-3.4%	-2.4%	-2.4%	-2.3%
-1.7%	-3.5%	-2.8%	-2.5%	-2.4%	-2.9%
-0.5%	-1.2%	-1.0%	-1.4%	-0.6%	-0.6%
-0.4%	0.1%	0.3%	1.2%	0.3%	0.3%
1.0%	0.6%	-0.1%	0.3%	1.0%	0.7%
1.1%	1.2%	0.7%	1.1%	1.6%	1.5%
1.5%	1.3%	1.0%	0.7%	1.9%	1.5%

(e) 4 PM

1.5%	0.9%	1.7%	1.3%	1.5%	2.5%
1.3%	0.6%	1.3%	1.0%	0.9%	1.4%
0.4%	0.3%	-0.2%	0.7%	1.1%	0.5%
1.0%	0.2%	-0.1%	0.0%	0.5%	0.0%
-0.6%	-0.5%	-1.1%	-0.8%	-1.3%	-1.1%
-2.7%	-2.3%	-2.9%	-2.8%	-2.6%	-2.0%
-2.2%	-2.7%	-3.4%	-2.6%	-3.2%	-3.2%
-1.3%	-1.2%	-0.3%	-0.5%	-1.1%	-0.5%
0.6%	0.2%	0.4%	0.1%	0.1%	0.6%
0.8%	0.6%	0.5%	0.8%	1.1%	0.0%
1.2%	1.0%	0.7%	1.5%	0.8%	1.5%
1.5%	2.0%	1.6%	1.4%	1.5%	1.8%

Example: 2-high central module, sunny day

(a) 8 AM

0.3%	0.1%	0.3%	0.1%	0.5%	0.1%
-0.1%	0.1%	-0.2%	0.4%	0.3%	0.4%
0.2%	-0.5%	0.3%	-0.1%	0.3%	-0.1%
-0.3%	-0.2%	0.2%	-0.1%	0.2%	0.0%
0.3%	0.3%	-0.2%	0.0%	0.2%	-0.1%
0.2%	0.2%	-0.1%	0.2%	0.2%	0.0%
0.1%	0.0%	-0.3%	-0.3%	0.0%	-0.1%
0.1%	-0.3%	-0.4%	0.2%	0.0%	-0.1%
-0.4%	0.4%	-0.1%	-0.1%	-0.1%	-0.4%
0.2%	-0.2%	0.2%	0.0%	0.1%	-0.1%
-0.1%	-0.3%	0.2%	-0.2%	-0.1%	-0.2%
-0.2%	-0.3%	-0.3%	-0.4%	-0.4%	0.7%

(b) 10 AM

2.9%	2.9%	2.5%	3.1%	2.6%	3.3%
2.3%	2.4%	1.9%	2.4%	1.7%	2.4%
1.3%	1.5%	1.7%	1.9%	1.7%	1.4%
0.6%	0.8%	0.7%	1.6%	0.9%	0.7%
-0.1%	0.5%	0.0%	0.4%	0.3%	-0.2%
-0.2%	-0.5%	-0.1%	0.0%	0.0%	-0.4%
-0.6%	-0.7%	-0.6%	-0.5%	-0.8%	-0.5%
-1.1%	-0.9%	-1.0%	-0.6%	-1.2%	-1.3%
-1.5%	-1.6%	-1.1%	-1.4%	-1.0%	-1.3%
-1.4%	-1.4%	-1.0%	-1.3%	-1.5%	-1.8%
-1.6%	-1.3%	-1.8%	-1.1%	-1.4%	-1.7%
-1.3%	-1.7%	-2.0%	-1.8%	-1.8%	-1.6%

(c) 12 PM

2.4%	1.8%	1.6%	2.2%	2.4%	2.4%
1.5%	2.0%	1.4%	1.3%	1.8%	1.8%
1.6%	1.3%	1.4%	1.4%	1.0%	1.6%
0.8%	0.5%	0.8%	0.7%	0.8%	0.8%
0.4%	0.5%	0.2%	0.8%	0.5%	0.5%
0.2%	0.5%	0.1%	0.5%	-0.1%	-0.4%
-1.0%	0.2%	-0.1%	0.0%	-0.1%	-0.2%
-0.3%	-0.3%	-0.3%	-1.0%	-0.6%	-0.5%
-0.6%	-0.8%	-0.6%	0.1%	-0.4%	-1.2%
-1.3%	-1.1%	-0.8%	-0.5%	-0.9%	-0.7%
-1.5%	-1.4%	-1.2%	-2.1%	-1.6%	-1.6%
-2.8%	-3.1%	-2.8%	-3.0%	-2.7%	-2.5%

(d) 2 PM

0.5%	0.5%	0.6%	0.3%	1.0%	0.2%
0.8%	1.0%	0.5%	0.6%	0.4%	0.3%
0.4%	0.2%	0.5%	-0.1%	0.9%	0.4%
0.2%	0.1%	0.3%	0.8%	0.1%	0.3%
0.5%	0.1%	0.1%	0.4%	0.2%	0.6%
-0.1%	0.4%	0.5%	0.1%	-0.2%	0.5%
0.0%	0.3%	0.1%	0.2%	0.7%	0.2%
-0.5%	0.0%	0.0%	0.3%	-0.2%	-0.2%
0.3%	0.0%	-0.6%	0.4%	0.0%	0.1%
0.0%	-0.4%	0.1%	-0.4%	-0.1%	-0.4%
-1.0%	-1.2%	-0.7%	-0.6%	-0.4%	-1.3%
-1.4%	-1.4%	-1.3%	-1.7%	-1.1%	-1.2%

(e) 4 PM

0.1%	-0.1%	-0.1%	-0.2%	-0.5%	0.0%
0.0%	0.1%	-0.4%	0.1%	-0.1%	0.3%
-0.4%	0.3%	-0.2%	-0.6%	0.2%	0.1%
0.1%	0.1%	0.1%	-0.1%	0.1%	-0.2%
-0.2%	0.0%	0.2%	0.4%	0.4%	0.0%
0.0%	-0.3%	0.0%	-0.1%	0.2%	0.2%
0.5%	0.3%	0.3%	-0.2%	0.2%	0.4%
0.1%	0.3%	-0.1%	0.5%	-0.1%	-0.1%
0.2%	-0.1%	0.0%	0.3%	0.0%	0.2%
0.0%	0.1%	-0.2%	0.1%	-0.1%	-0.2%
-0.5%	0.4%	0.2%	0.0%	0.1%	-0.2%
-0.5%	-0.3%	-0.5%	-0.2%	0.2%	-0.6%

0.5%	0.3%	0.6%	0.1%	0.5%	0.4%
-0.3%	0.0%	0.0%	-0.1%	0.2%	0.0%
-0.2%	0.0%	-0.5%	0.0%	0.1%	-0.1%
-0.1%	-0.2%	-0.5%	-0.2%	0.1%	0.4%
0.1%	0.3%	0.0%	0.4%	0.1%	-0.4%
-0.1%	0.0%	0.1%	0.0%	0.0%	0.1%
0.0%	0.1%	0.2%	-0.2%	0.1%	-0.4%
-0.1%	0.1%	-0.2%	0.0%	0.2%	-0.2%
-0.2%	-0.4%	0.2%	-0.2%	0.1%	0.1%
0.0%	0.0%	-0.1%	0.5%	0.0%	0.5%
0.0%	-0.1%	-0.4%	0.1%	-0.3%	-0.3%
-0.3%	-0.2%	0.2%	-0.2%	0.2%	0.1%

-1.4%	-0.9%	-0.7%	-0.7%	-1.0%	-0.7%
-0.4%	-0.2%	-0.3%	-0.6%	-0.4%	-0.4%
0.4%	0.0%	0.1%	0.5%	-0.2%	0.2%
-0.2%	-0.3%	-0.1%	-0.1%	0.2%	-0.2%
-0.3%	0.0%	-0.1%	0.2%	0.2%	0.3%
-0.4%	0.0%	-0.2%	0.0%	0.3%	0.4%
0.0%	0.1%	0.2%	0.0%	0.4%	0.5%
-0.1%	0.2%	0.2%	0.6%	0.1%	0.3%
-0.2%	0.8%	-0.1%	0.1%	0.6%	0.3%
0.1%	0.7%	0.4%	-0.1%	0.6%	0.2%
0.3%	-0.1%	0.1%	0.0%	0.0%	0.1%
0.2%	-0.1%	-0.3%	0.3%	0.2%	0.5%

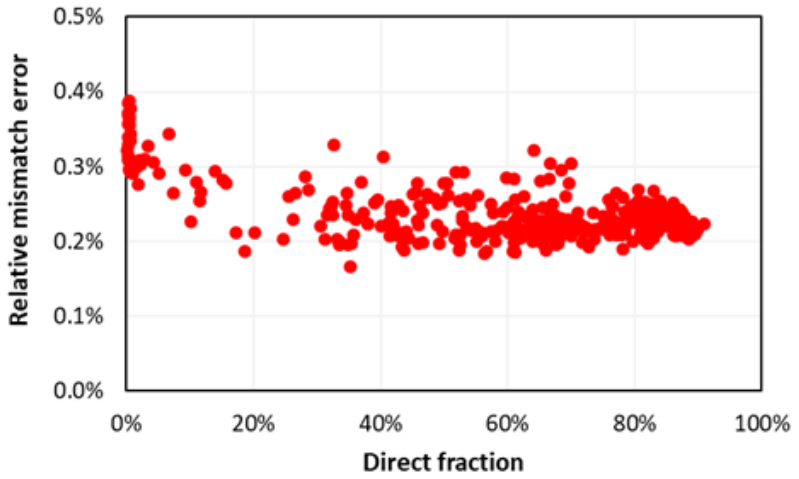
-2.7%	-3.2%	-3.4%	-3.0%	-2.4%	-2.6%
-1.2%	-1.8%	-1.3%	-0.9%	-1.9%	-1.5%
-0.7%	-1.1%	-1.0%	-1.0%	-1.0%	-1.4%
-0.7%	-1.0%	-0.5%	-0.9%	-0.6%	-0.4%
-0.3%	0.4%	-0.3%	-0.3%	-0.5%	-0.5%
0.0%	0.4%	0.0%	0.0%	0.0%	-0.6%
-0.2%	0.0%	0.5%	0.4%	-0.2%	0.0%
0.8%	0.0%	0.5%	0.9%	0.4%	0.6%
0.8%	0.7%	0.8%	0.3%	0.3%	0.7%
1.2%	1.0%	0.9%	1.4%	0.9%	1.4%
1.7%	1.5%	1.2%	2.2%	1.8%	1.8%
2.3%	2.1%	2.7%	2.3%	1.8%	2.5%

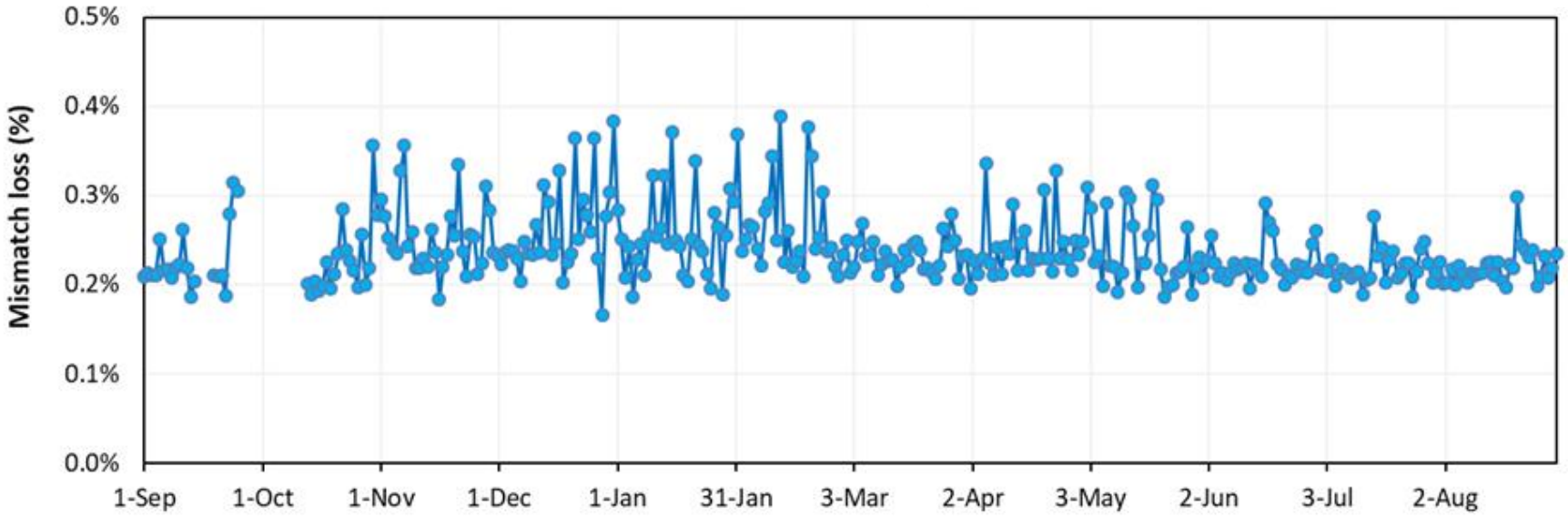
-1.7%	-1.9%	-2.0%	-1.8%	-2.1%	-1.6%
-1.9%	-1.2%	-1.4%	-1.4%	-1.2%	-1.5%
-1.0%	-1.1%	-1.4%	-1.9%	-1.3%	-1.7%
-1.0%	-1.0%	-1.2%	-1.7%	-1.7%	-1.5%
-0.9%	-1.3%	-1.1%	-0.4%	-0.5%	-1.2%
-1.1%	-0.3%	-0.2%	-0.3%	-1.0%	-0.4%
-0.4%	0.0%	-0.6%	-0.2%	-0.5%	0.3%
0.5%	0.1%	0.4%	0.4%	0.2%	-0.1%
0.9%	1.3%	0.8%	0.5%	0.9%	1.1%
1.1%	1.1%	1.6%	1.5%	1.4%	1.5%
2.5%	2.1%	2.0%	2.2%	2.8%	2.2%
3.4%	2.6%	3.2%	2.6%	2.8%	2.7%

-0.1%	-0.1%	0.0%	0.0%	-0.2%	0.5%
-0.3%	-0.5%	-0.4%	-0.2%	-0.3%	-0.4%
-0.2%	0.0%	0.1%	0.0%	-0.4%	0.0%
0.0%	-0.4%	-0.1%	0.1%	-0.4%	0.3%
0.1%	-0.1%	-0.5%	-0.2%	-0.2%	-0.2%
0.4%	0.0%	0.1%	0.0%	-0.3%	-0.1%
-0.4%	0.1%	0.0%	-0.3%	0.4%	-0.1%
0.4%	0.3%	0.2%	-0.4%	0.1%	-0.2%
0.1%	0.0%	0.6%	-0.1%	0.6%	0.2%
-0.1%	0.4%	0.2%	-0.1%	0.2%	0.2%
-0.1%	0.1%	0.4%	0.6%	0.1%	0.2%
0.0%	0.2%	0.7%	-0.2%	0.0%	0.1%

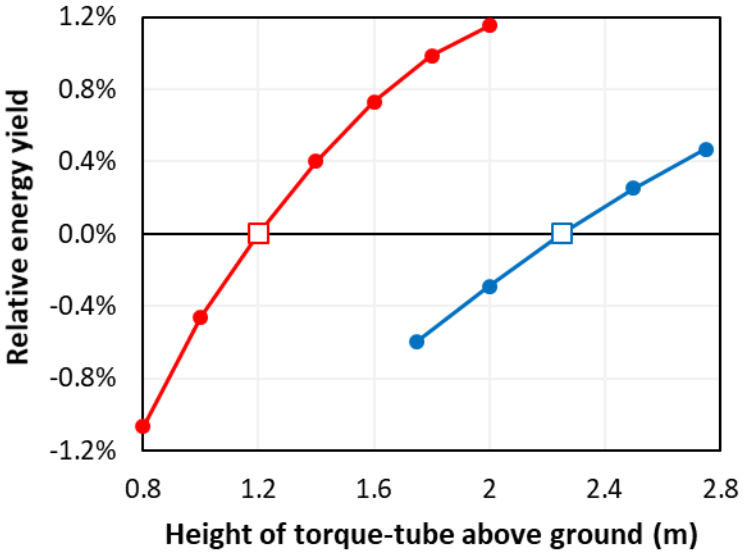
Mismatch loss – central module
(due to non-uniform illumination in module)

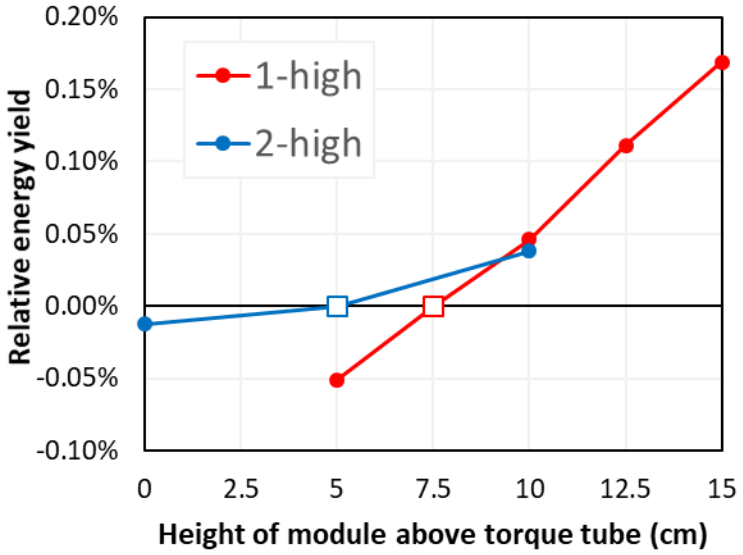
- For baseline cases
  - 0.23% for one-high system;
  - 0.1% for two-high system.
- Greater loss on diffuse days.

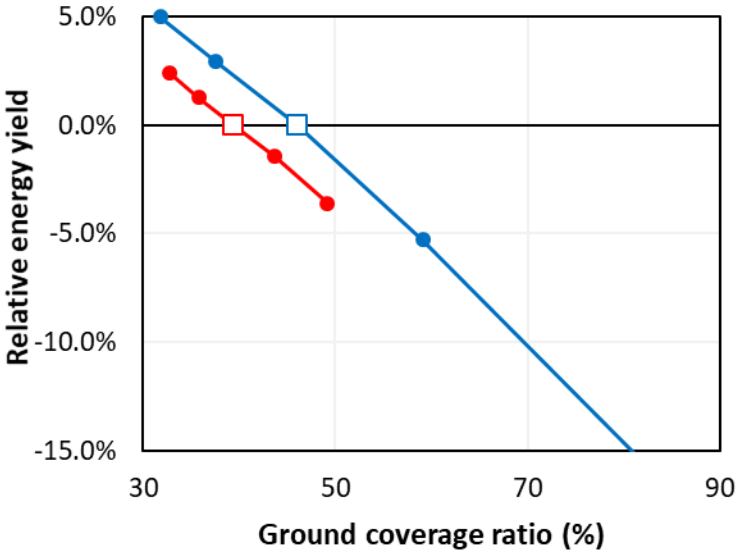


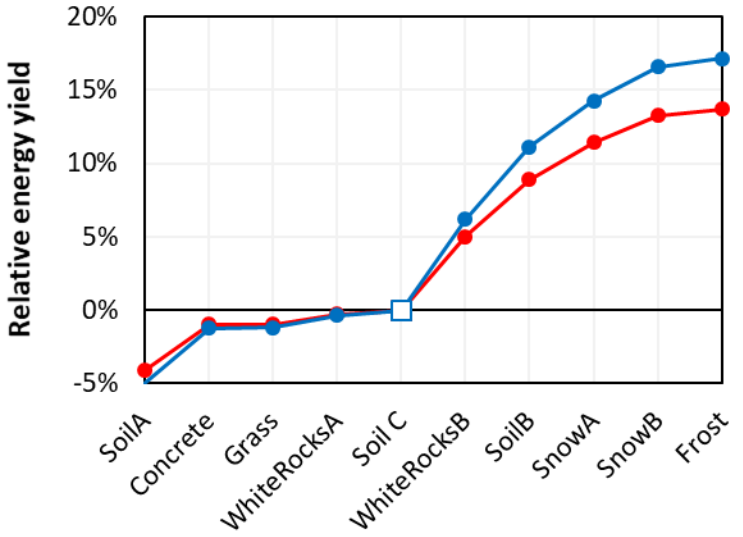


Evaluate different system configurations

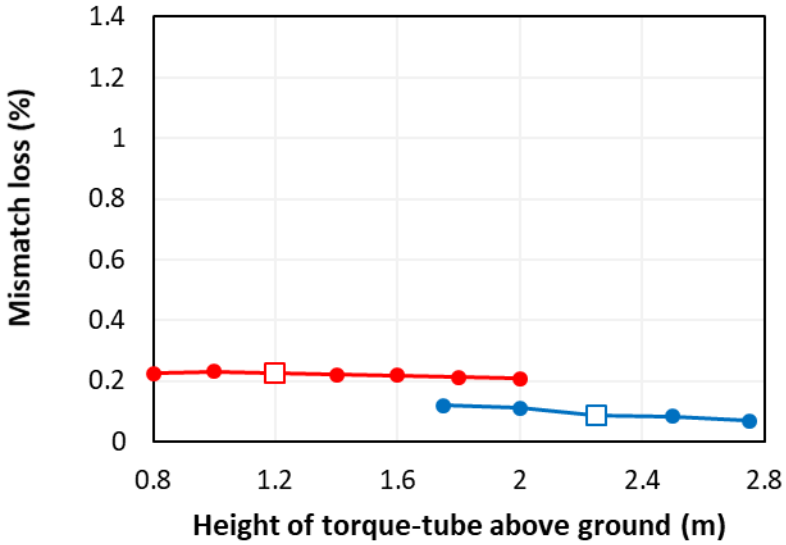


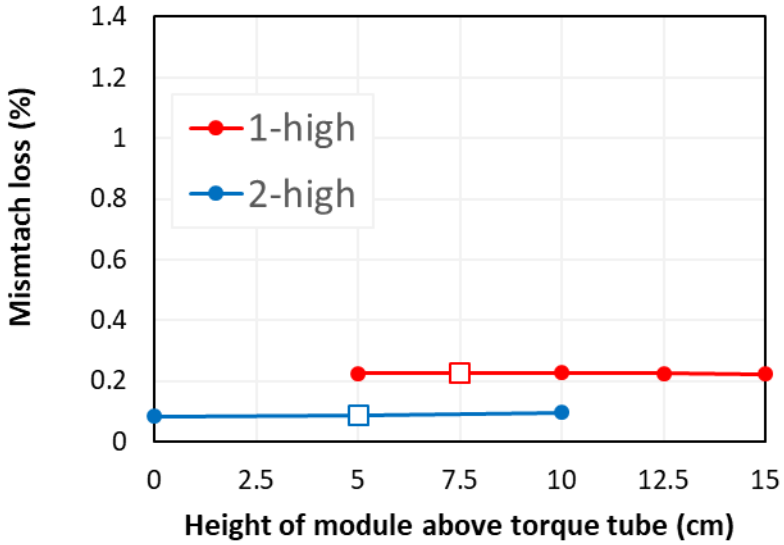


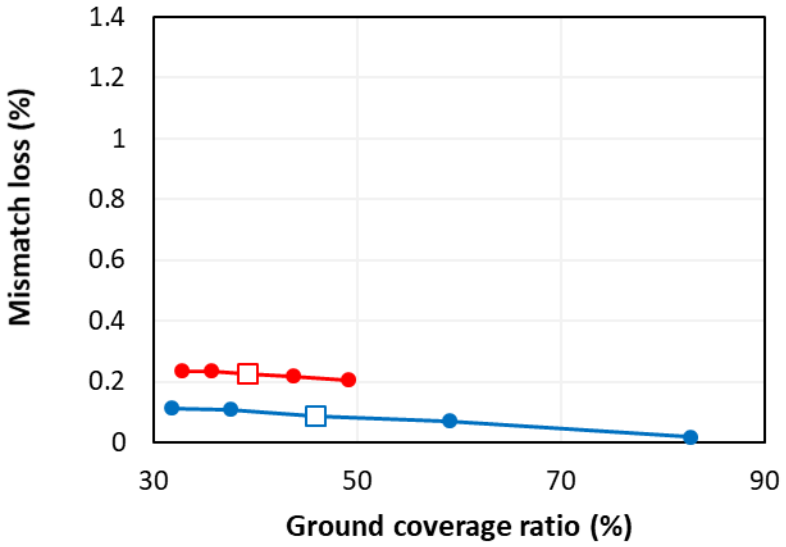


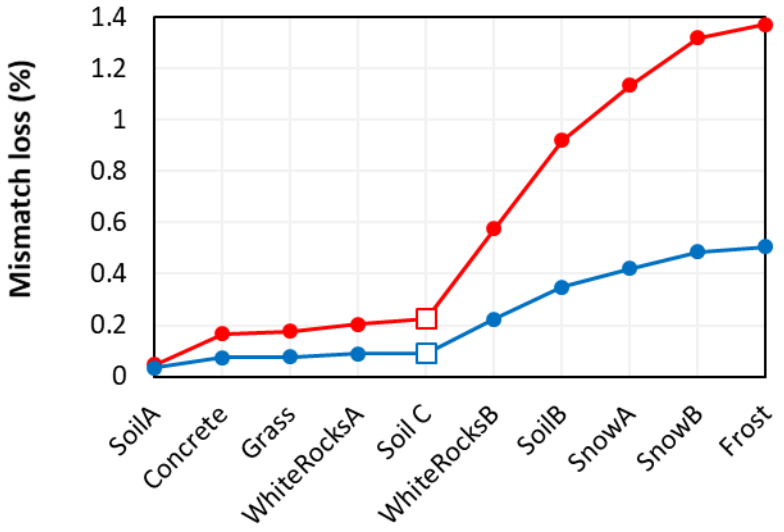


Evaluate different system configurations

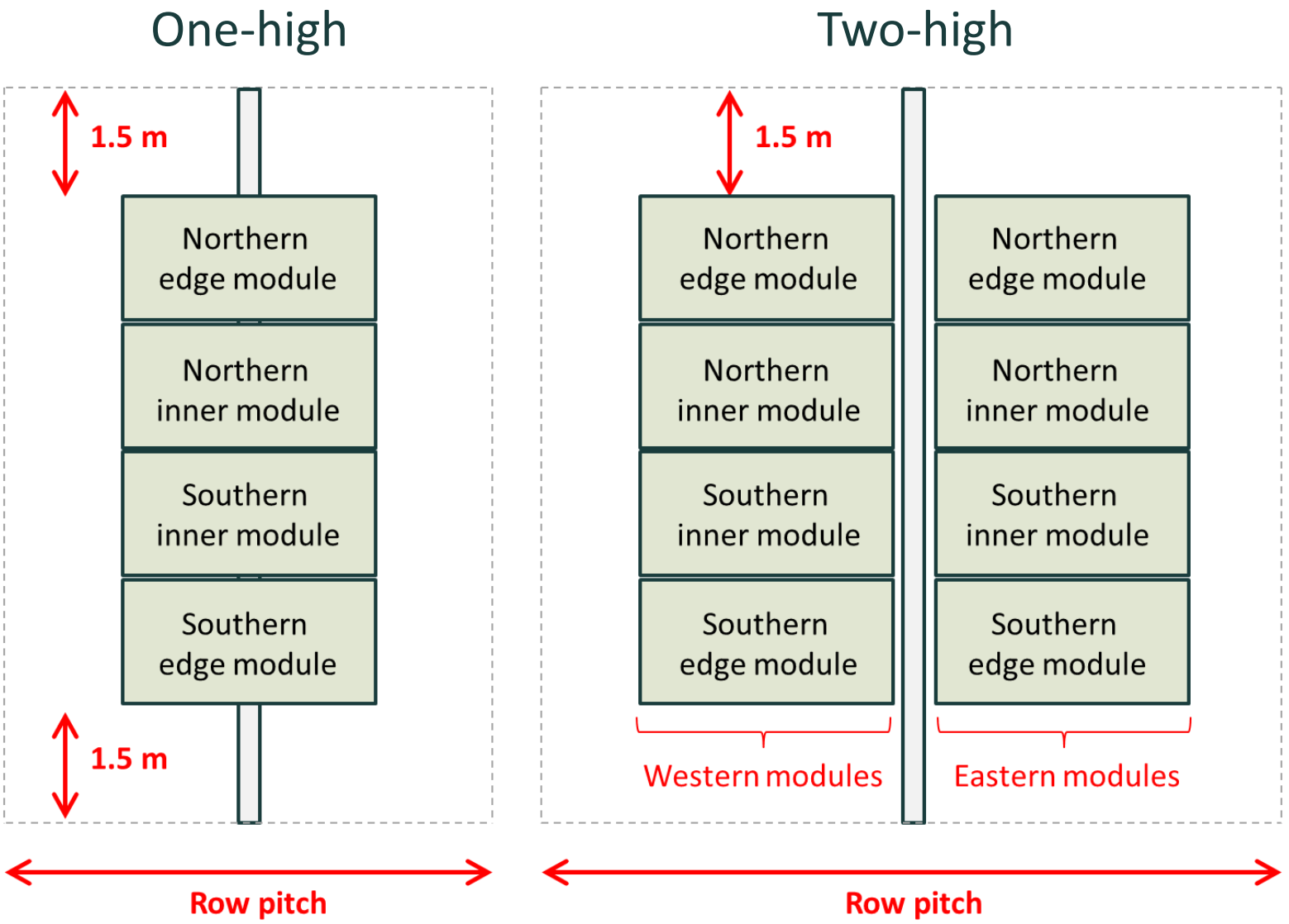




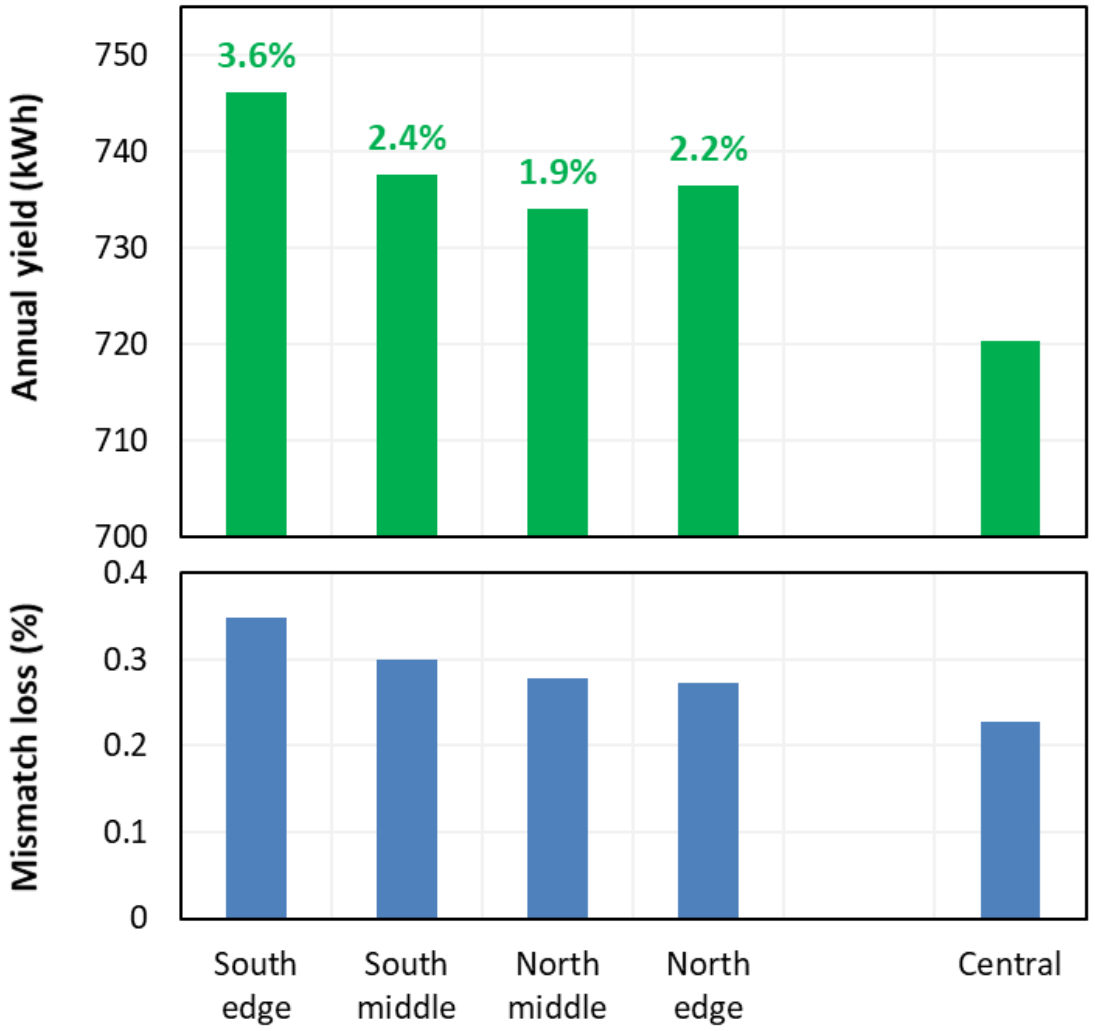




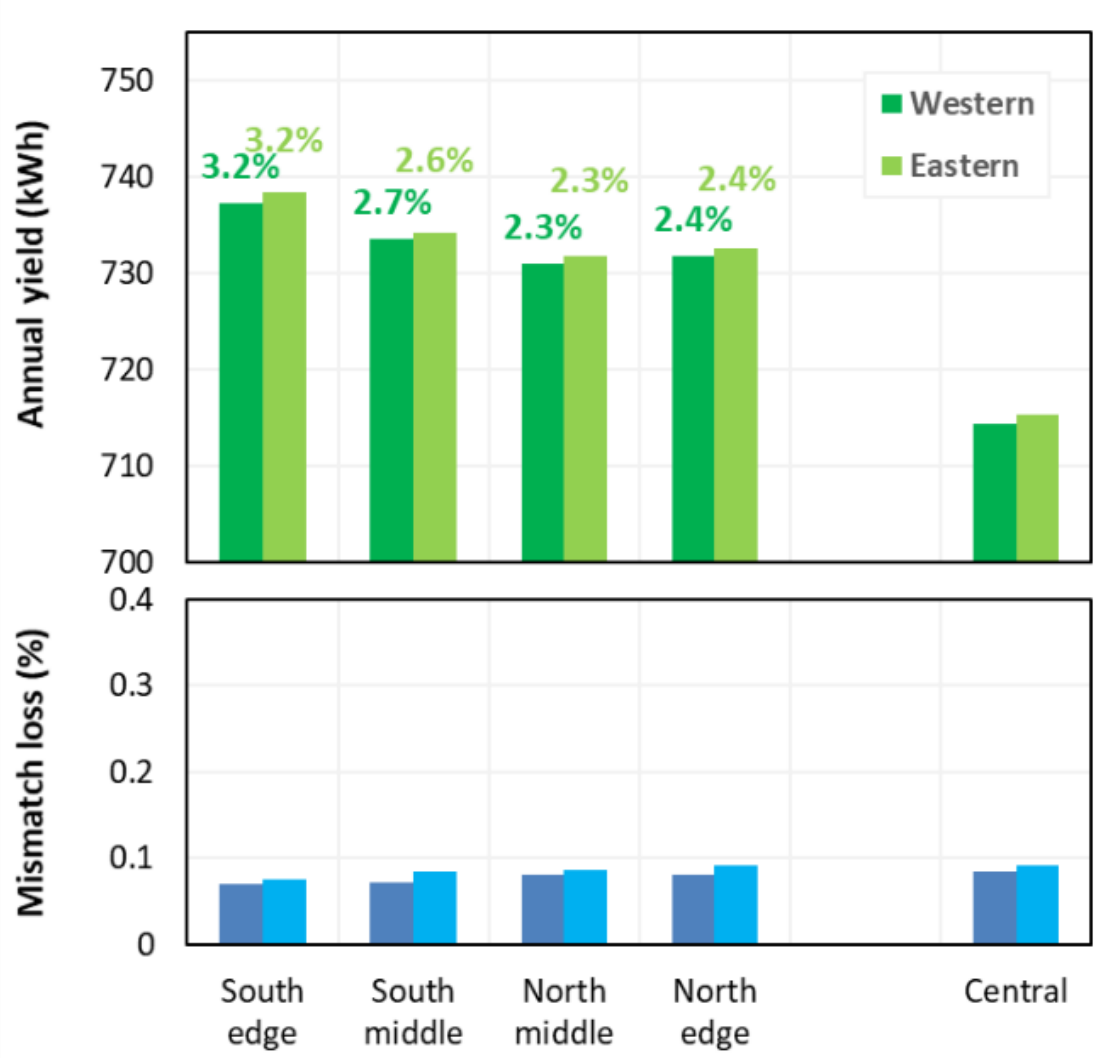
Edge modules



One-high


Annual yield (kWh)
750
740
730
720
710
700
3.6%
2.4%
1.9%
2.2%
Mismatch loss (%)
0.4
0.3
0.2
0.1
0
South edge
South middle
North middle
North edge
Central

Two-high


Annual yield (kWh)
750
740
730
720
710
700
Western
Eastern
3.2%
3.2%
2.6%
2.7%
2.3%
2.3%
2.4%
2.4%
Mismatch loss (%)
0.4
0.3
0.2
0.1
0
South edge
South middle
North middle
North edge
Central

Summary

- Annual yield solved by ray tracing to micron-level, accounting for
  - Spectral variability of direct and diffuse light,
  - Spectral and angular dependencies of ground, torque-tube and module,
  - Mismatch within a module due to non-uniform illumination.
- Results allow us to quantify advantages
  - system configurations,
  - module features,
  - simulation assumptions.
- Mismatch loss due to non-uniformity in 1-high configs is about:
  - 0.23% for our baseline conditions,
  - 2–3 times greater than two-high configs,
  - 50% greater for edge modules,
  - Depends strongly on albedo.

Thank you

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