Applying advanced ray tracing to predict the energy yield of bifacial systems with reduced uncertainty

PV ModuleTech 2018

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Perennial questions:

- How will different system configurations compare?
  - Bifacial vs monofacial?
  - 2D tracking vs 1D tracking vs static?
  - One-high vs two-high configurations?
  - One location vs another?
  - Good sunny years vs bad cloudy years?
  - Good days vs bad days? One albedo vs another? Etc… Etc…
- How would different modules perform in a particular system?
  - Conventional vs PERC vs HIT vs CdTe?
  - Binned cells vs non-binned cells?
  - Black silicon vs random pyramids vs isotexture?
  - Textured ribbons vs planar ribbons vs smart wires? Etc… etc…

How accurately can we predict answers to those questions?

Today's question:

- When predicting a system's energy yield, is it worth accounting for
  - spectral variability in the
    - incident spectrum
    - albedo
    - angular spectral response of module
  - mismatch in a module due to non-uniform illumination?
- The answer depends on
  - how much the PV system is influenced by those effects; and
  - how rapidly, easily, and accurately the effects can be simulated.

Today's talk:

A major advance in simulation that enables us to answer this questions.

Systems investigated

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

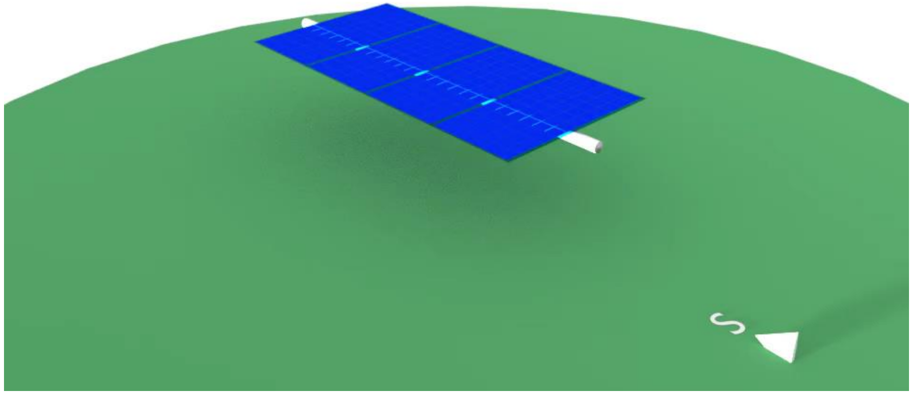
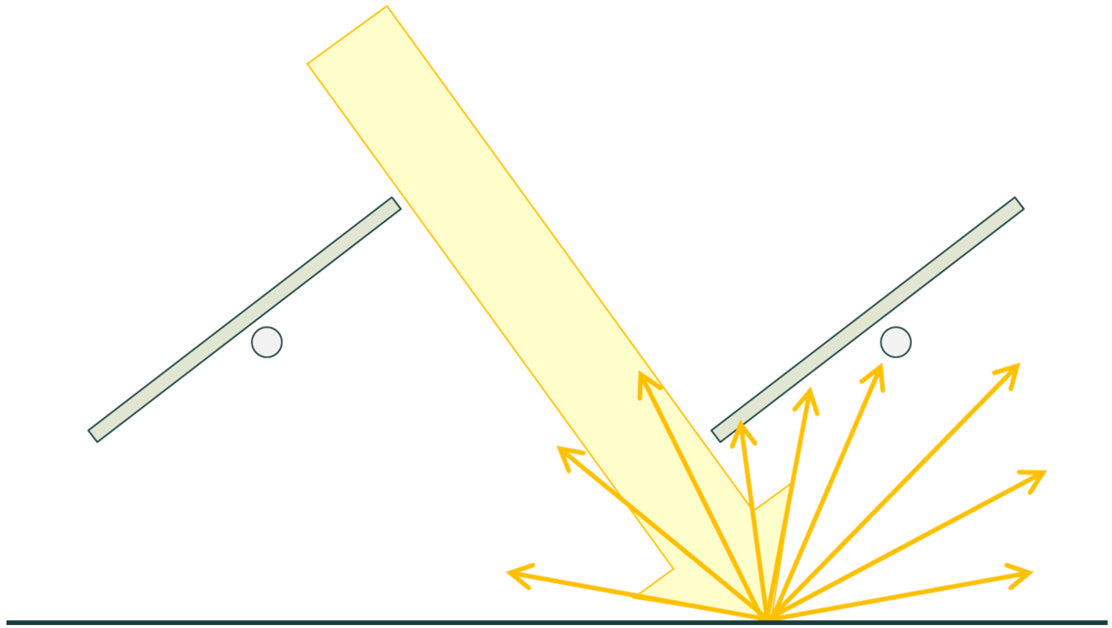


Image from https://www.nextracker.com

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

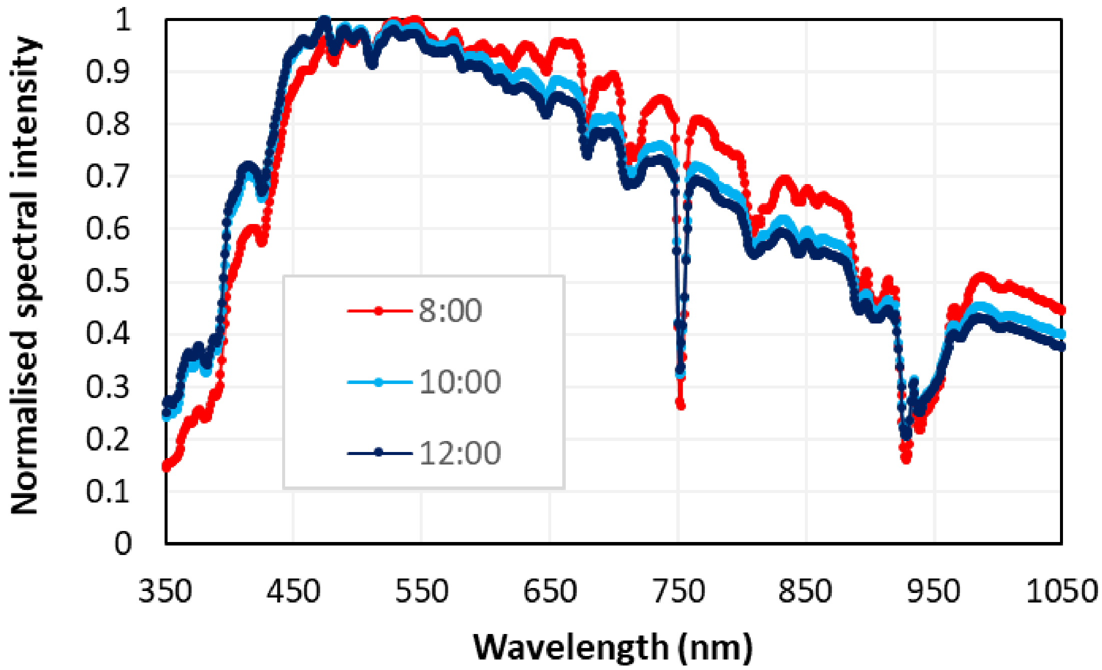
Challenge 1: Rear illumination

- Differs for direct and diffuse light.
- Direct light reflected more onto bottom of the module, depends on the time of day.
- Torque-tube shading.



Challenge 2: Spectral variability

- Solar spectrum changes throughout day & year



Data for direct illumination at Golden, CO, on 14-Mar-2018. Taken from NREL databases; A. Andreas, T. Stoffel; (1981). NREL Solar Radiation Research Laboratory (SRRL): Baseline Measurement System (BMS); Golden, Colorado (Data); NREL Report No. DA-5500-56488. http://dx.doi.org/10.5439/1052221

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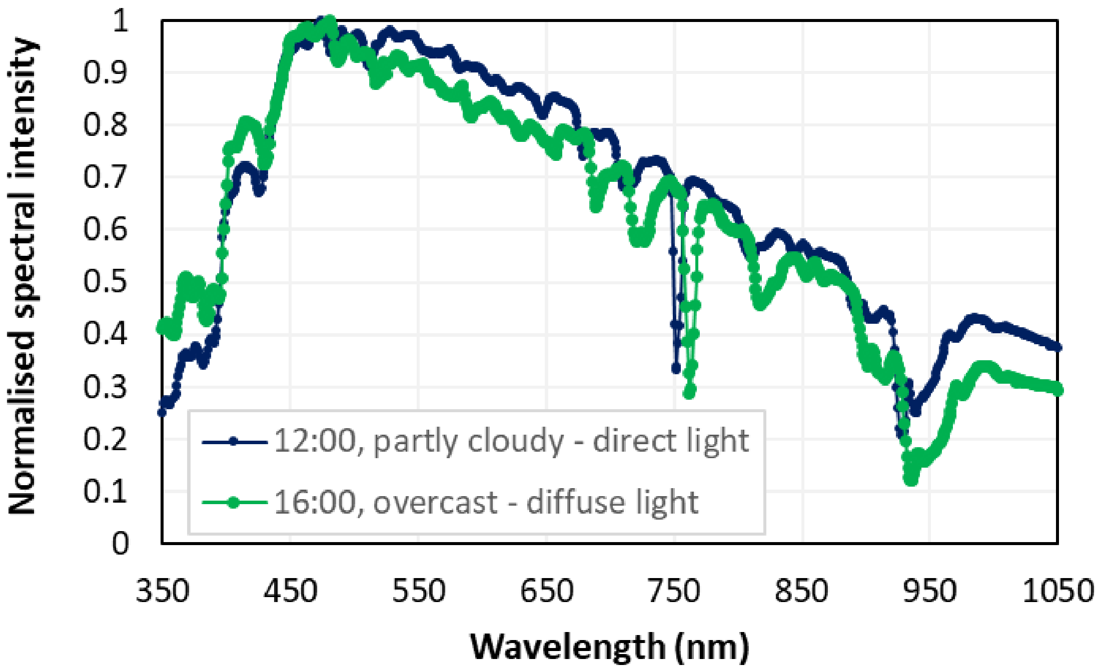

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Challenge 2: Spectral variability

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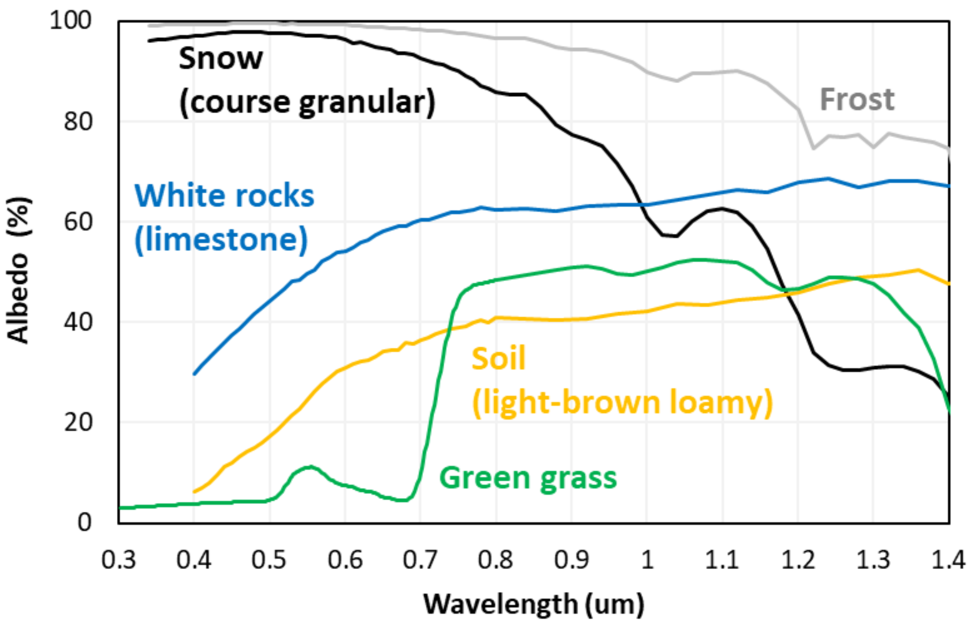
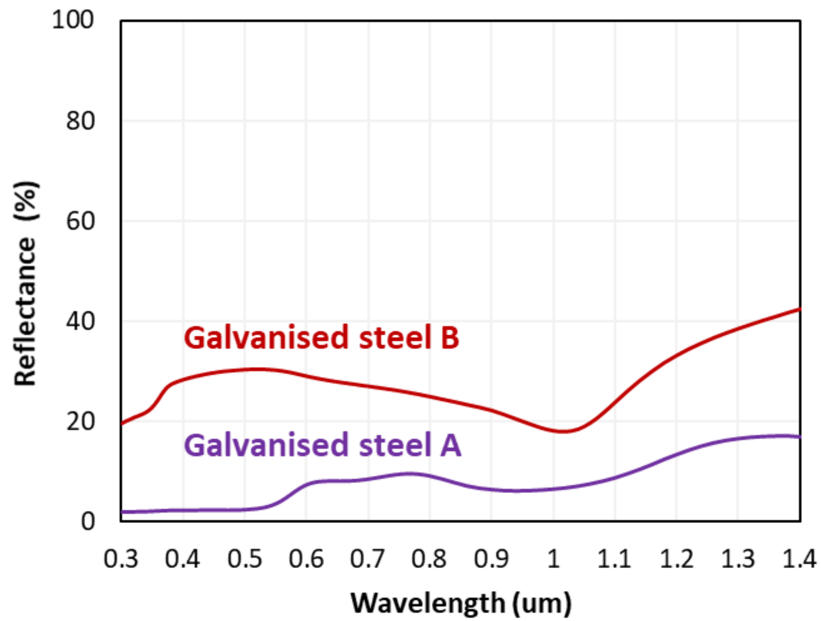
- Solar spectrum differs for direct and diffuse light.
- Reflectance of ground and torque-tube depend on wavelength.





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

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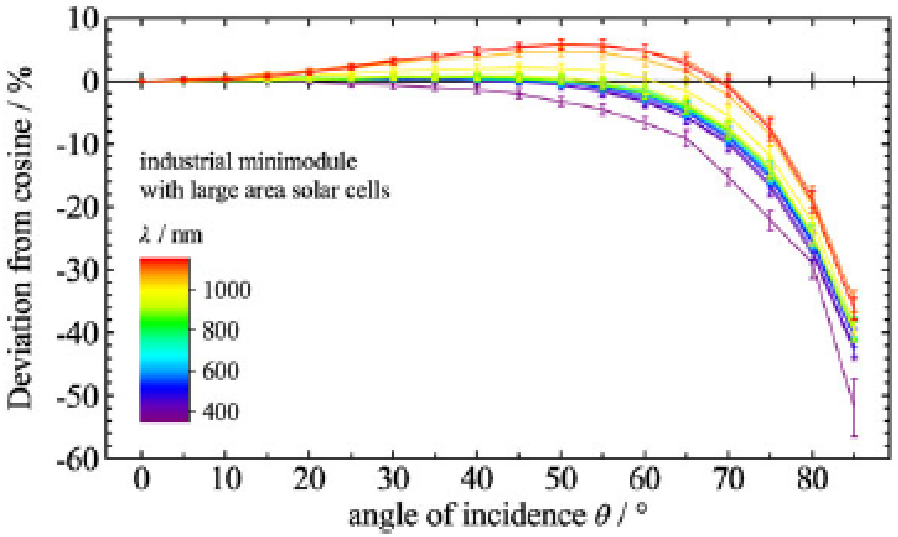
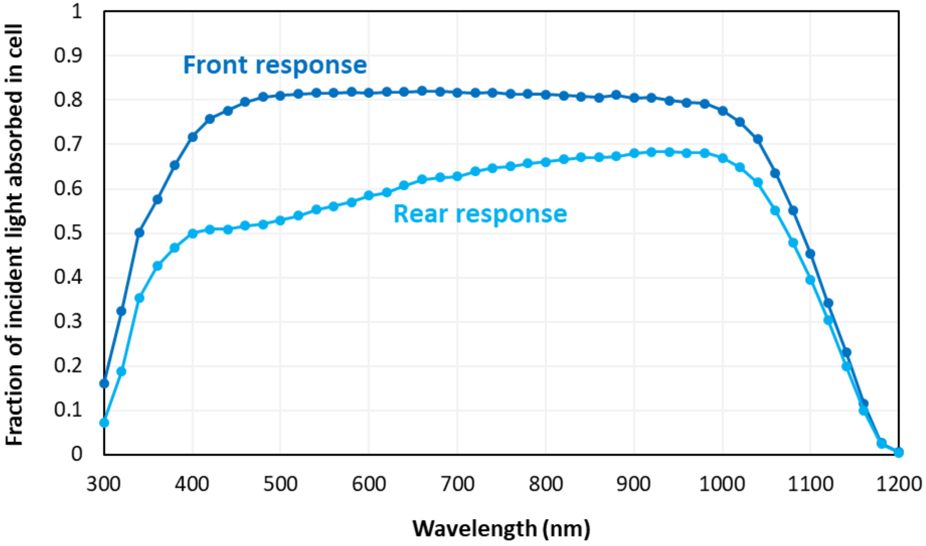
- Module's response depends on wavelength and incident angle.



Plag *et al.*, "Angular-dependent spectral responsivity—Traceable measurements on optical losses in PV devices," PIP, 2017.

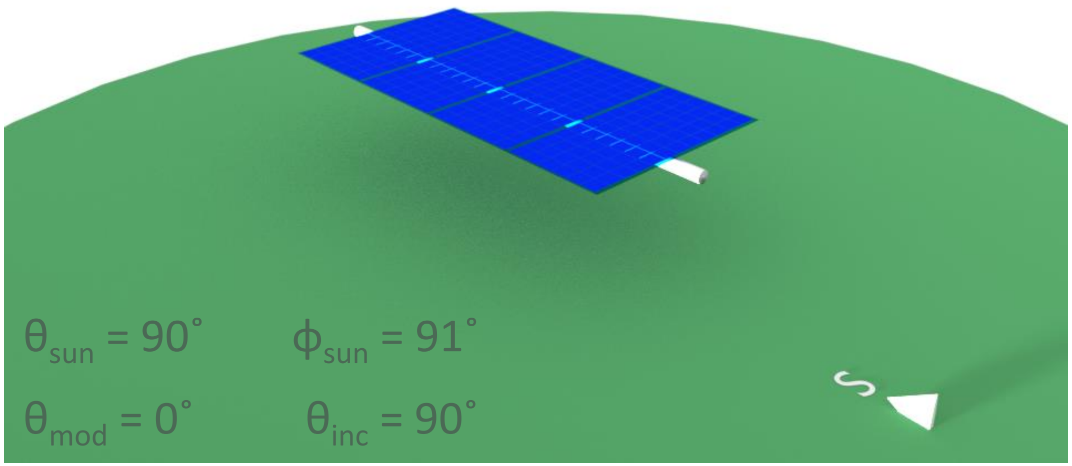
Challenge 2: Spectral variability

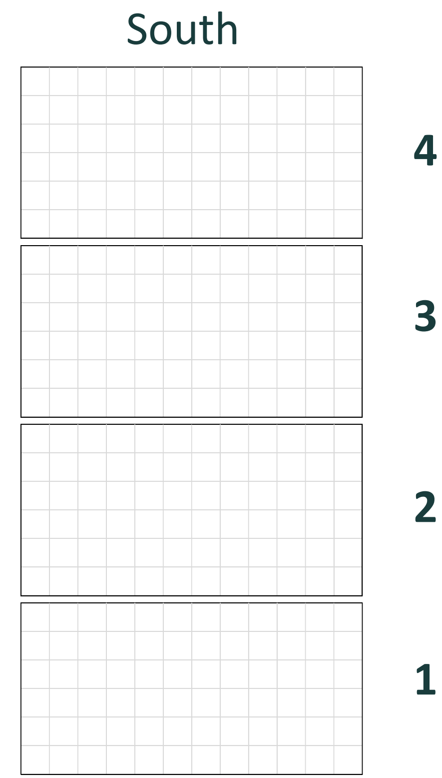
- Solar spectrum changes throughout day & year.
- Solar spectrum differs for direct and diffuse light.
- Reflectance of ground and torque-tube depend on wavelength.
- Module’s response depends on wavelength and incident angle.
- Module’s rear response differs to front response.

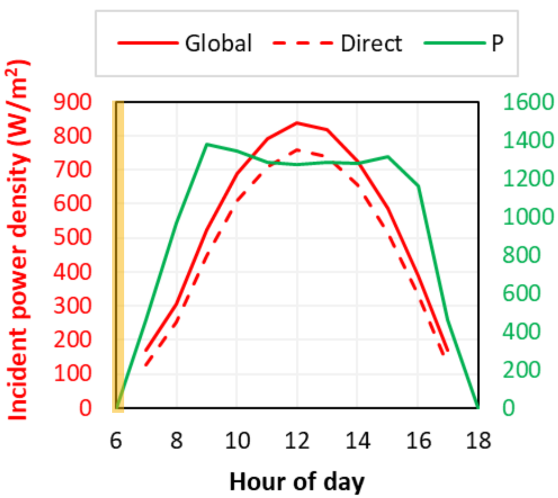


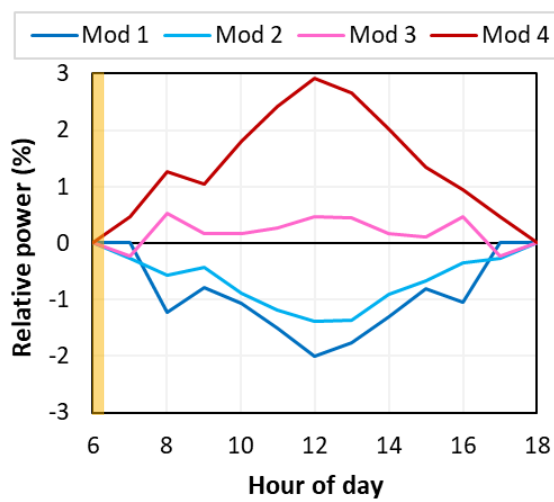
As simulated by PV Lighthouse for contemporary bifacial module under normal incidence.

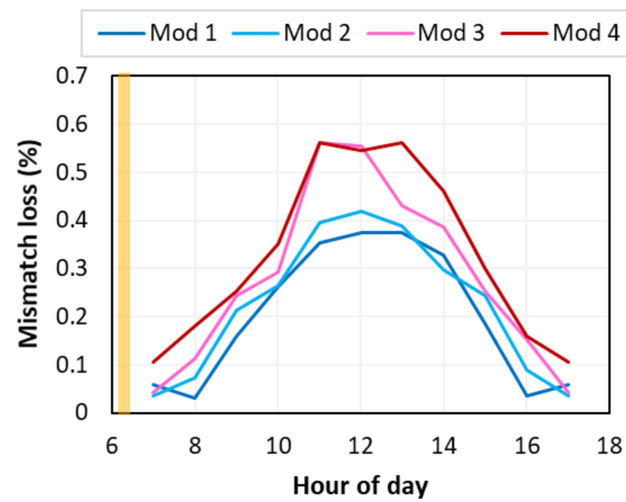
Challenge 3: Mismatch











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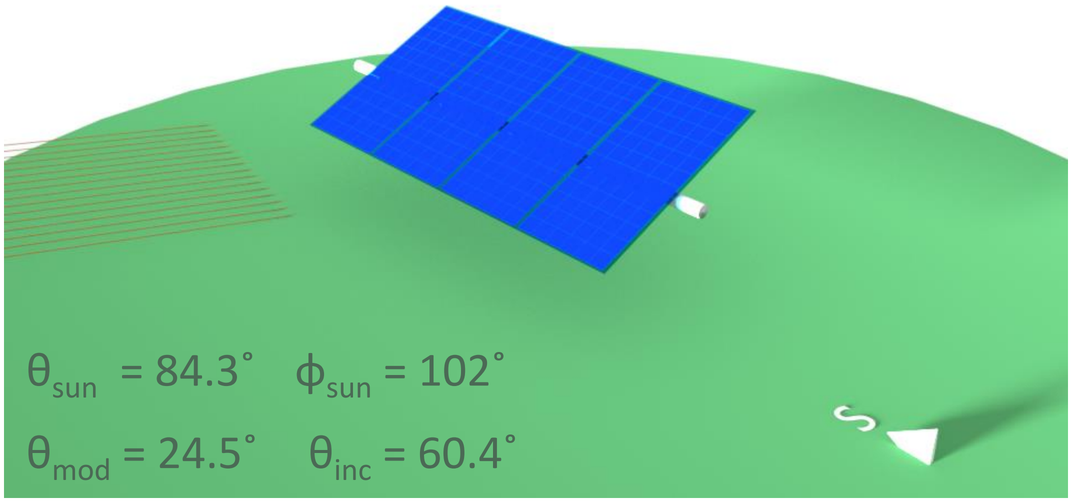

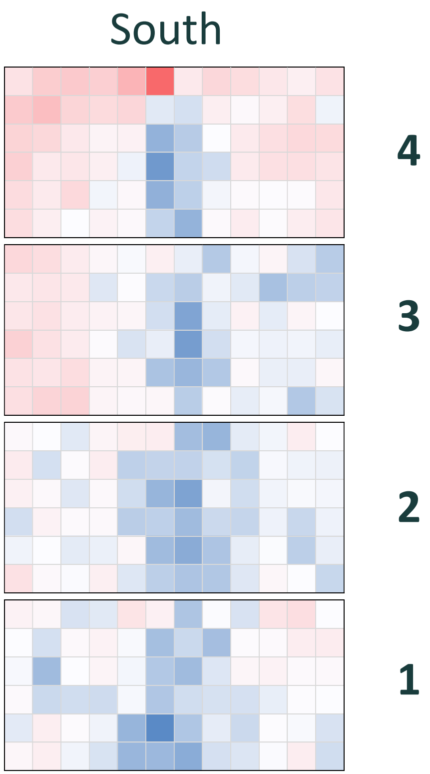

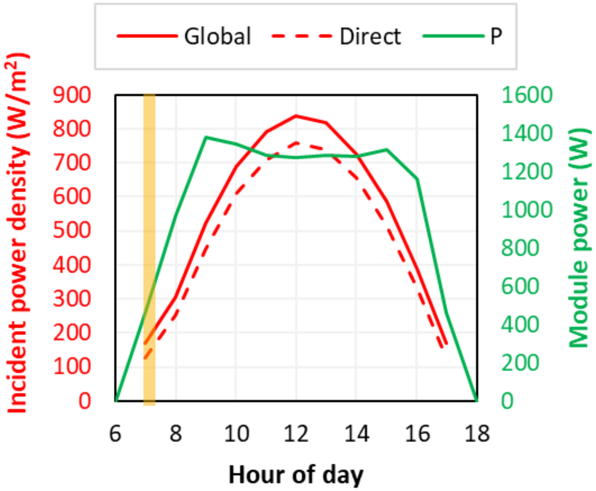

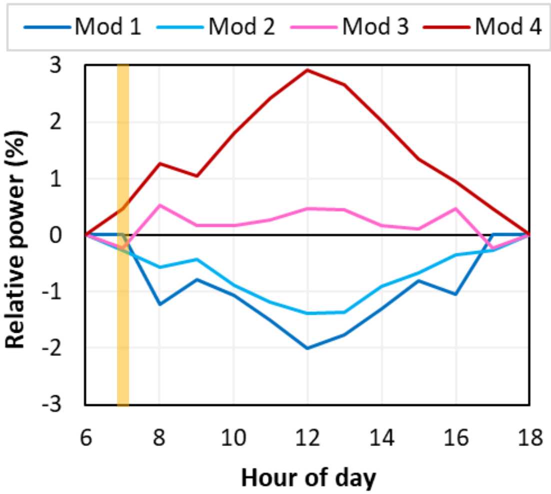

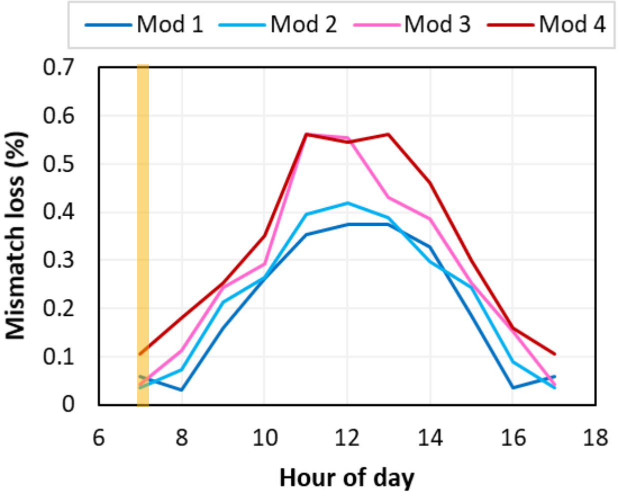

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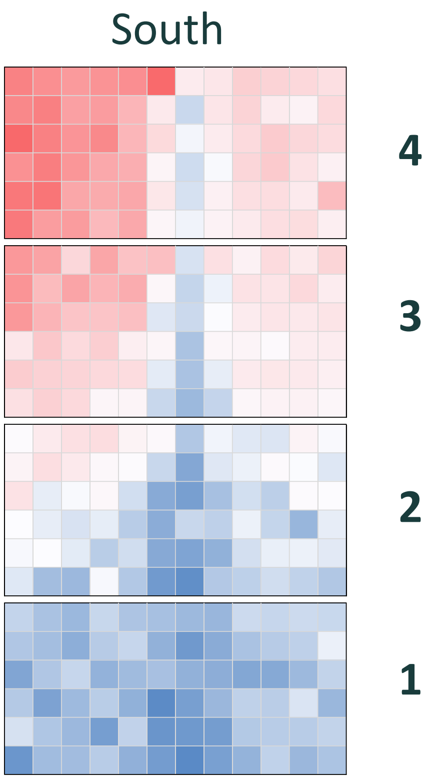

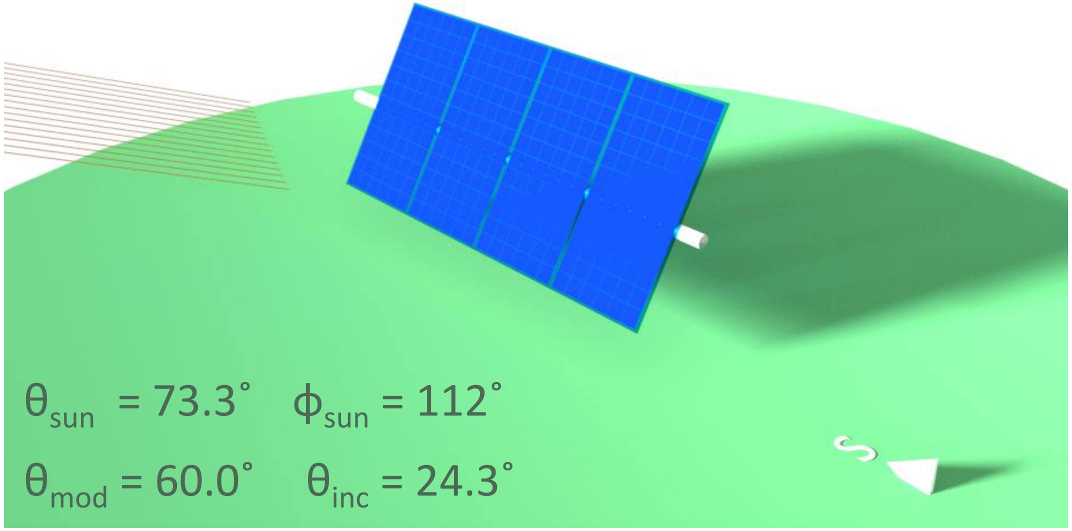

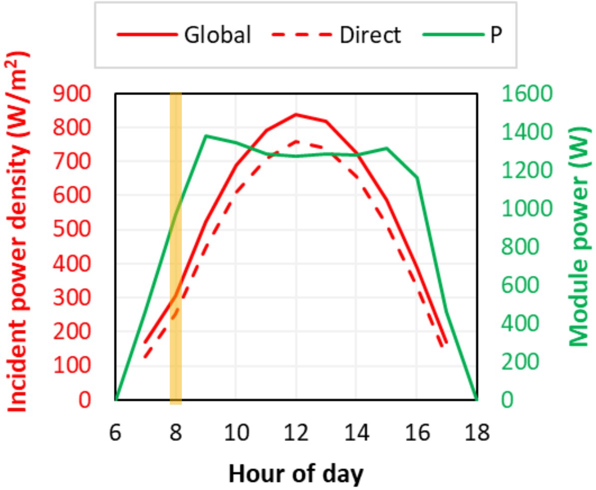

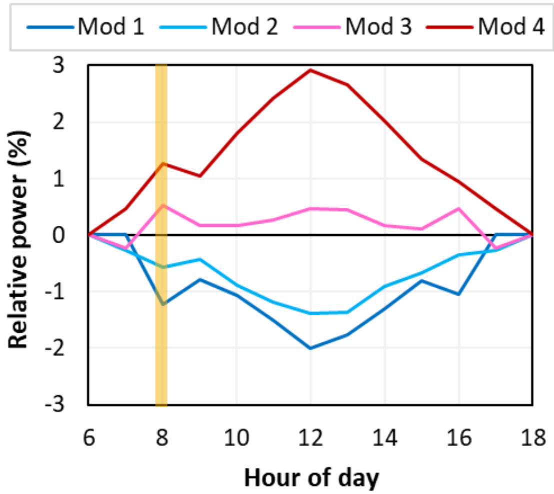

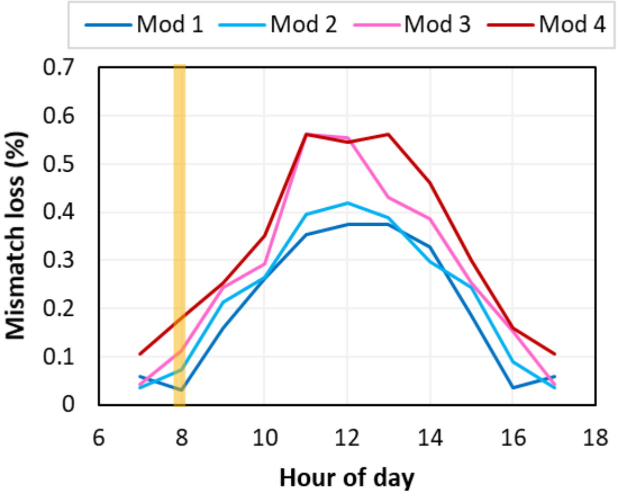

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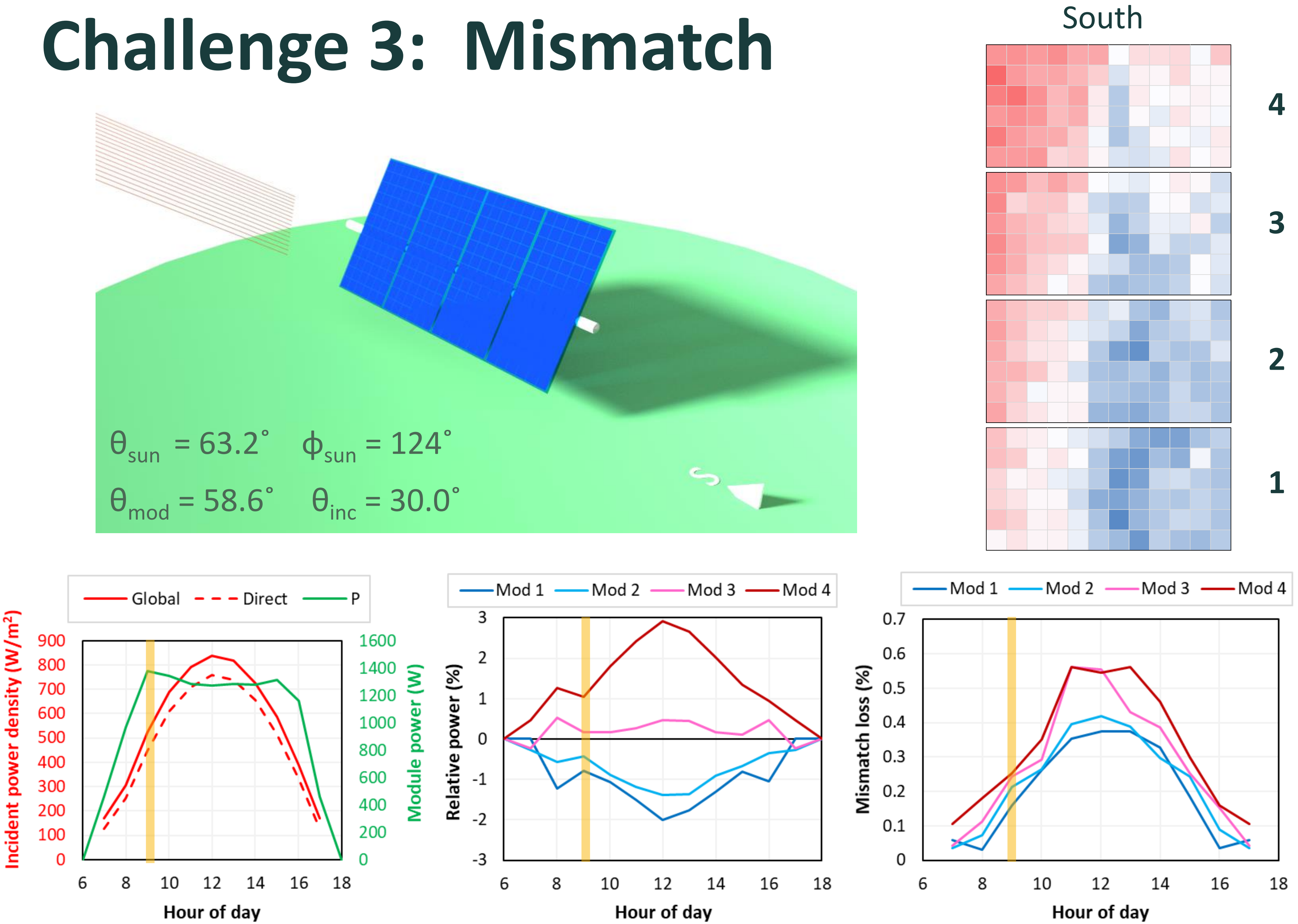

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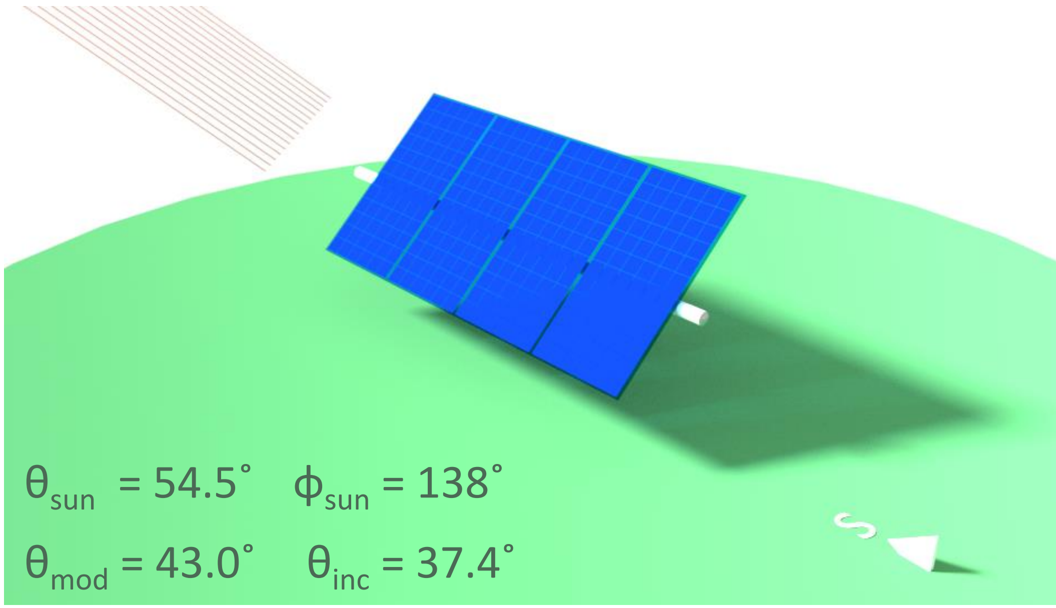

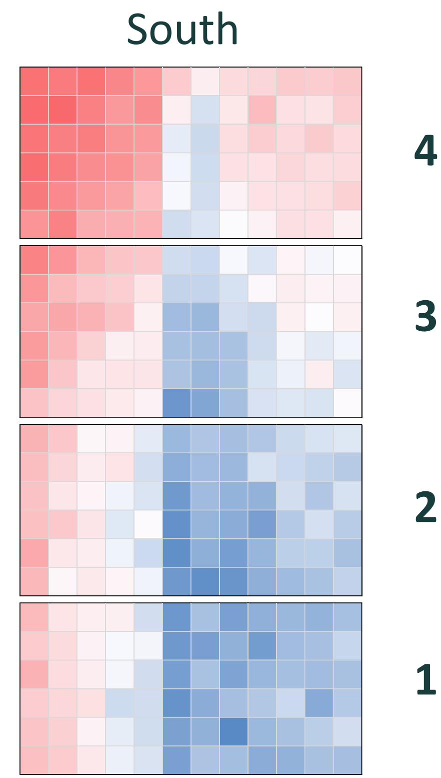

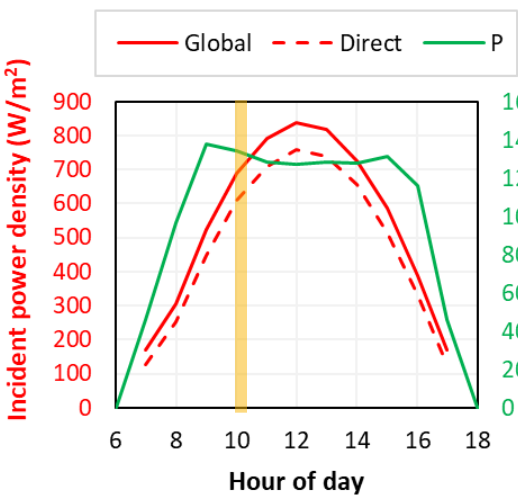

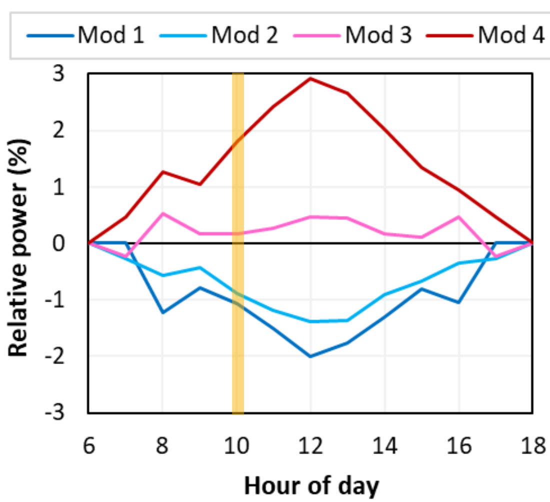

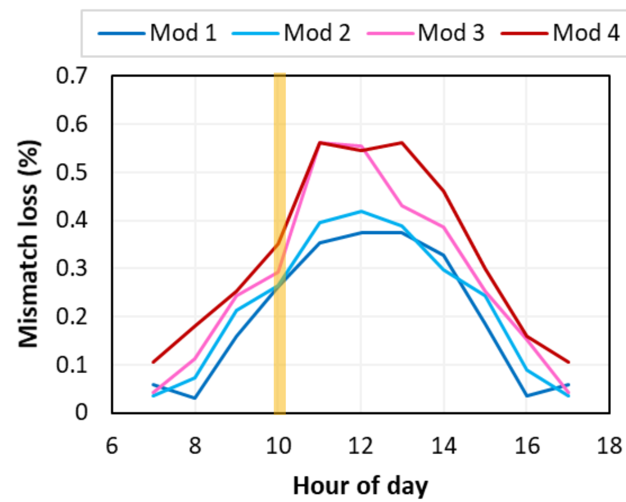

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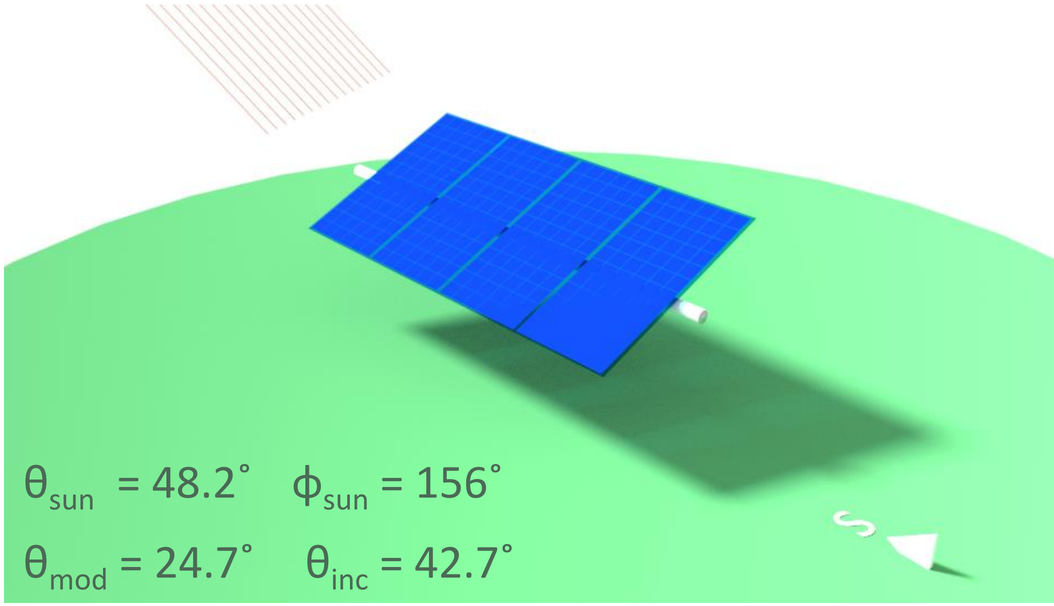

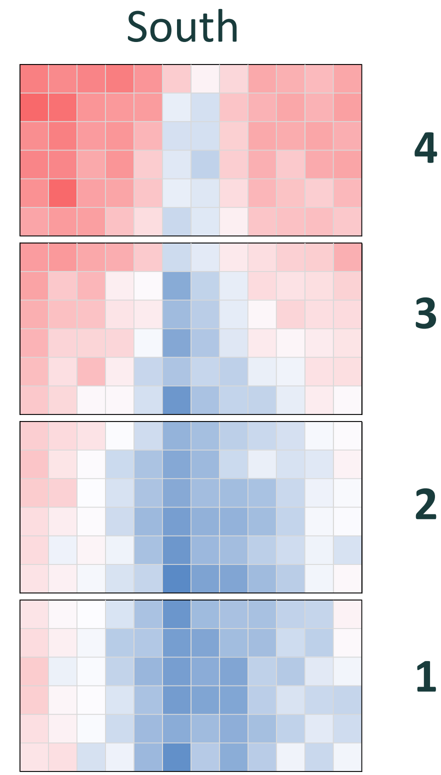

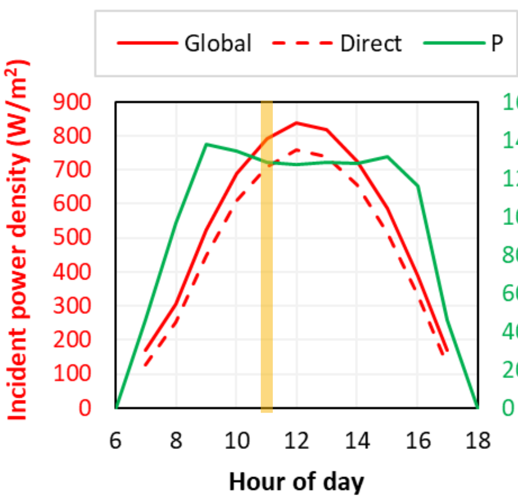

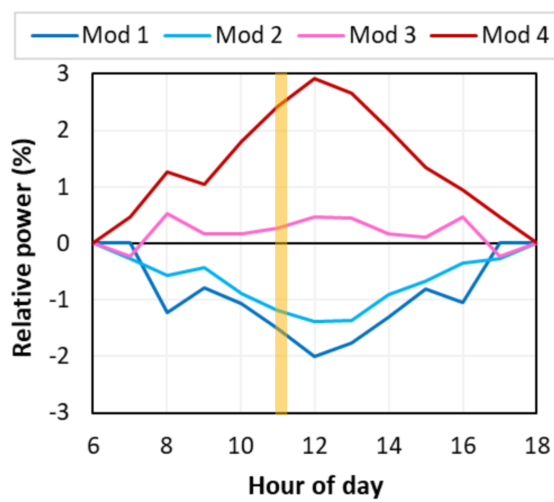

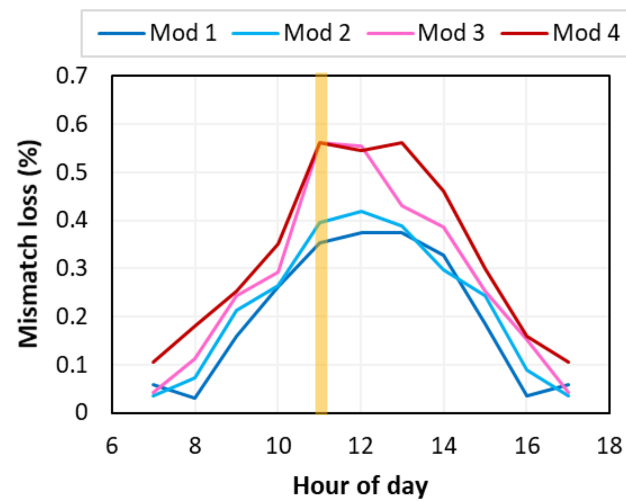

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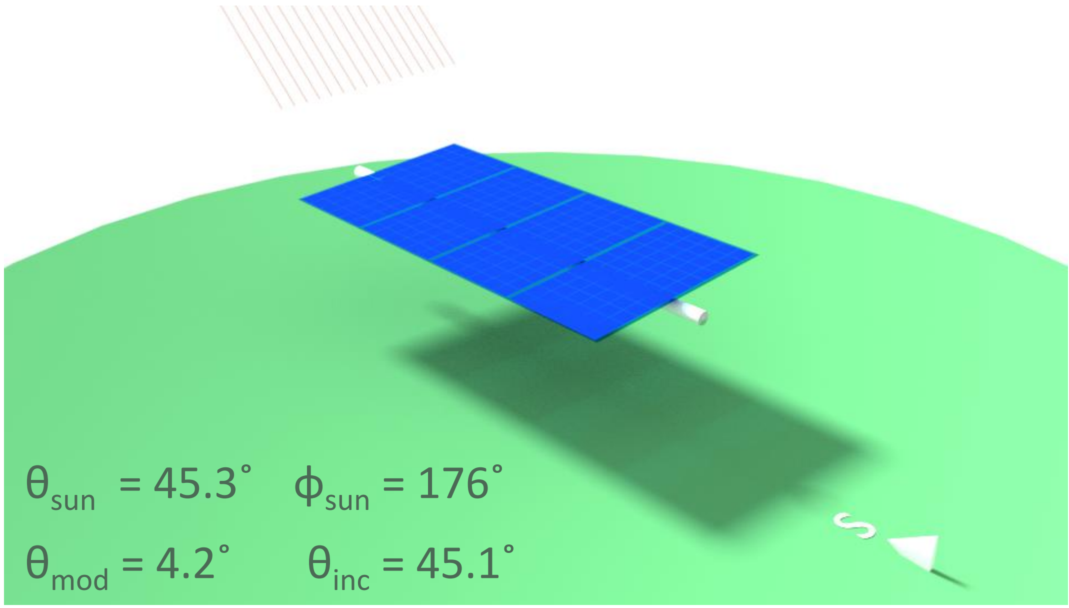

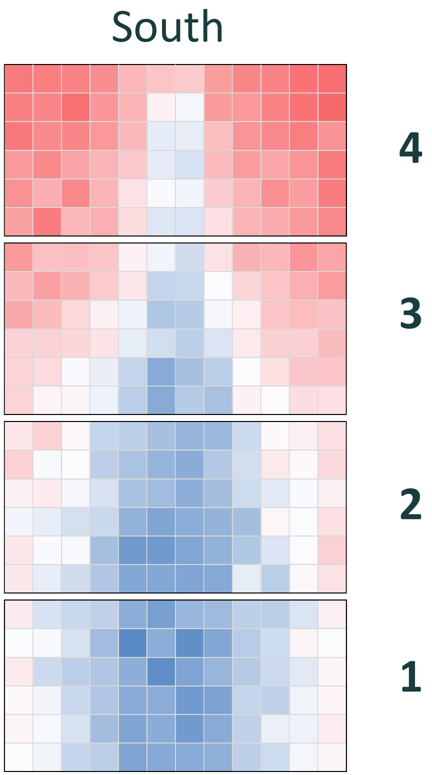

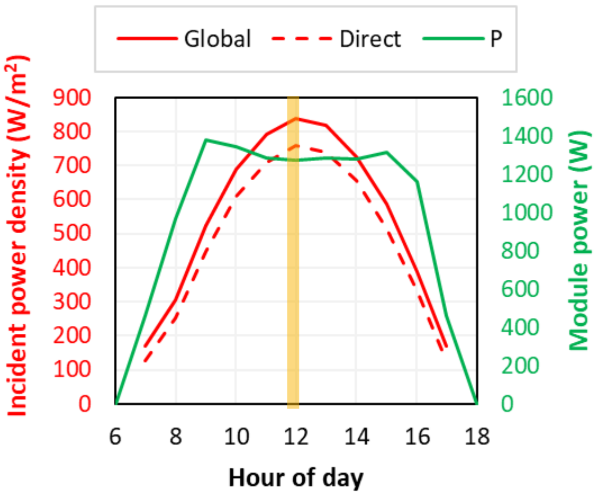

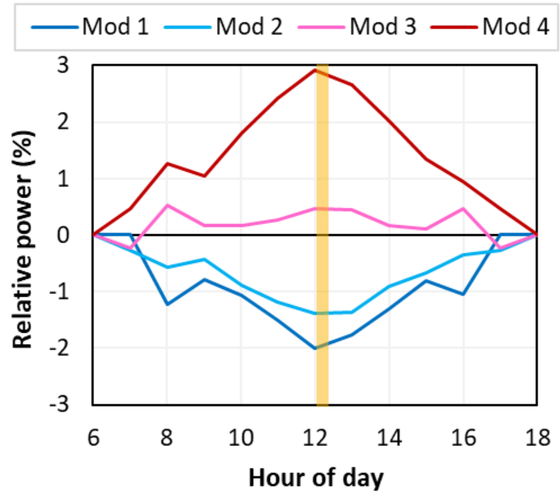

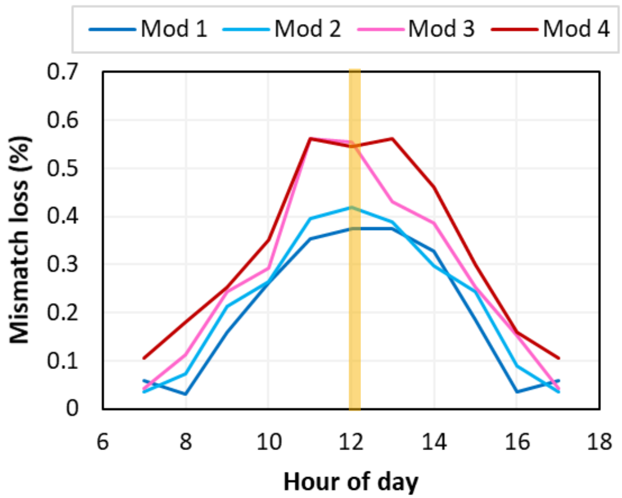

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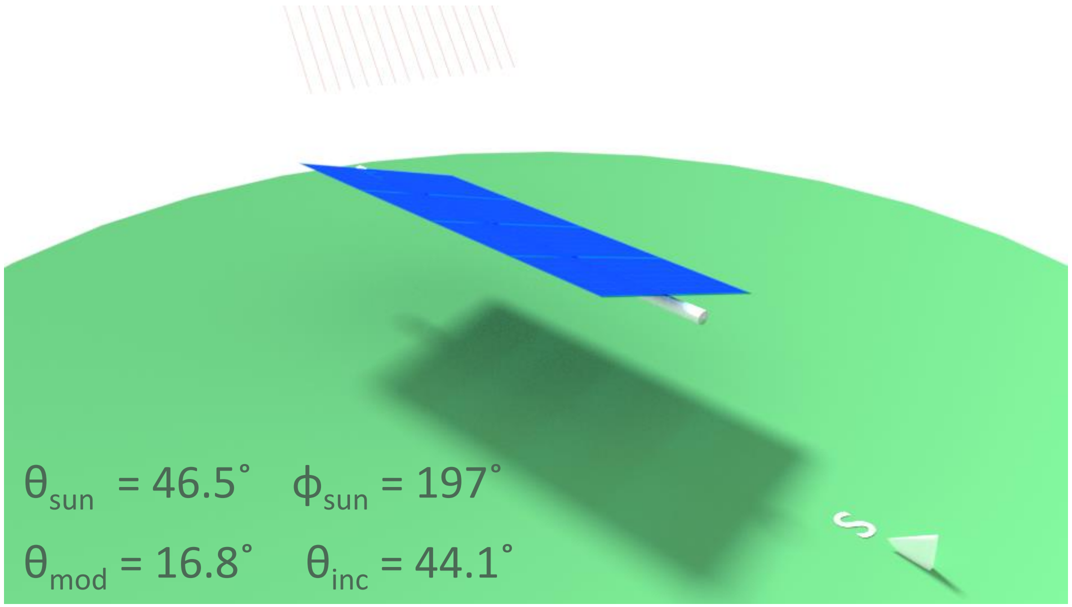

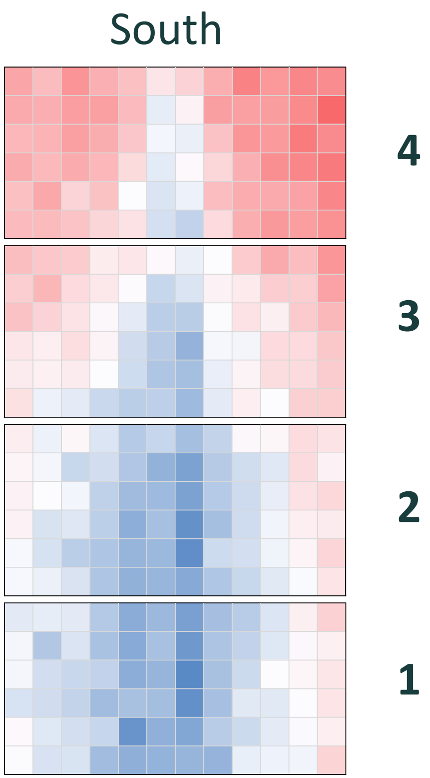

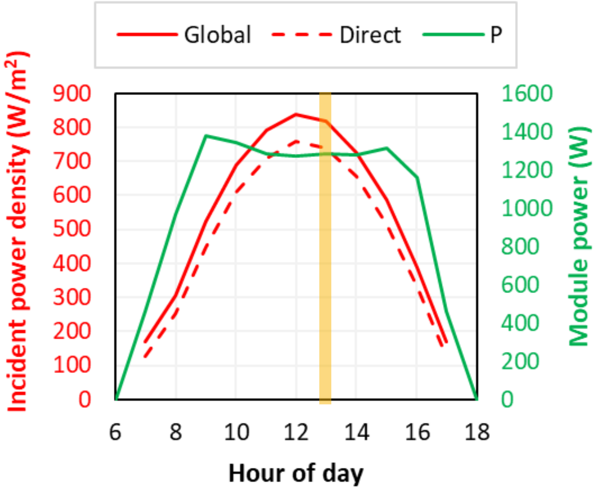

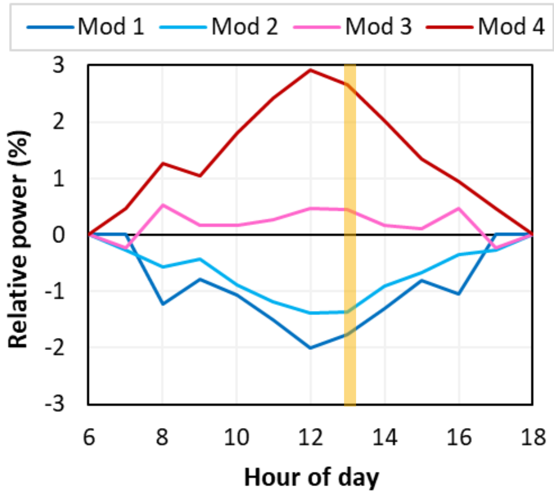

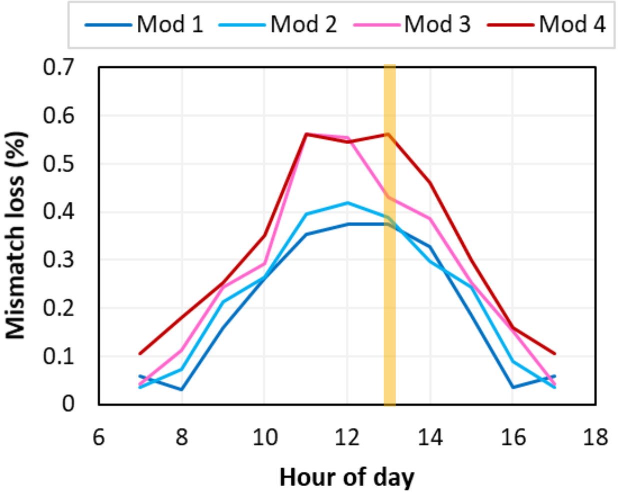

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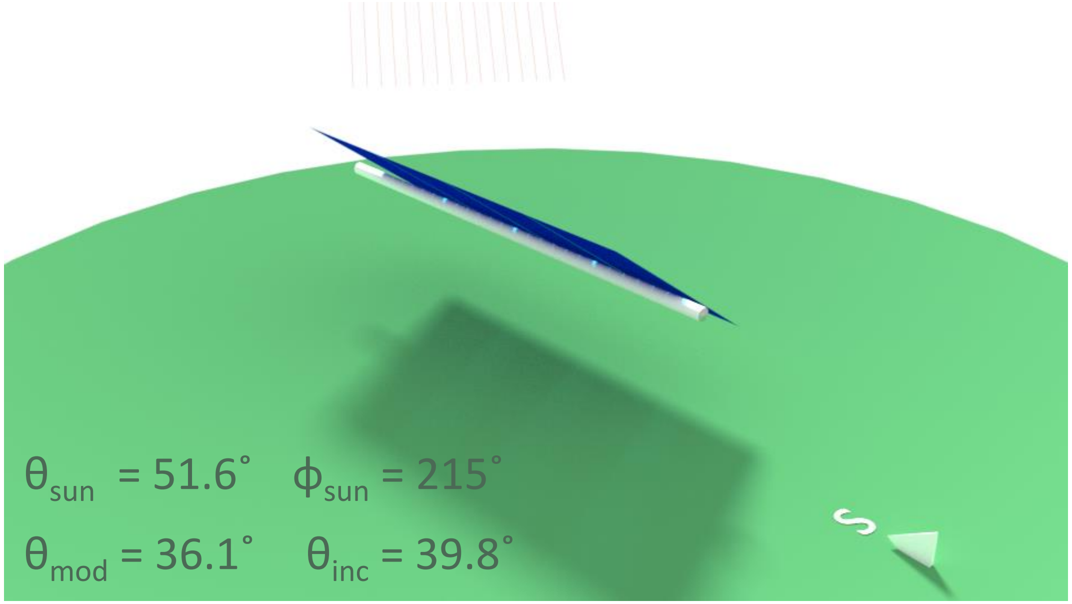

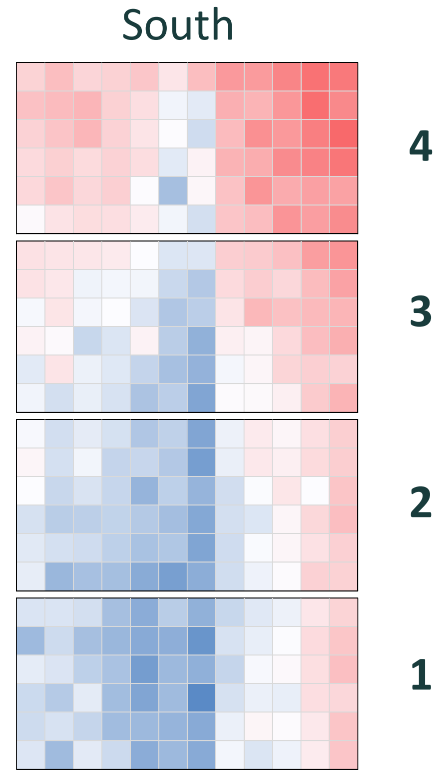

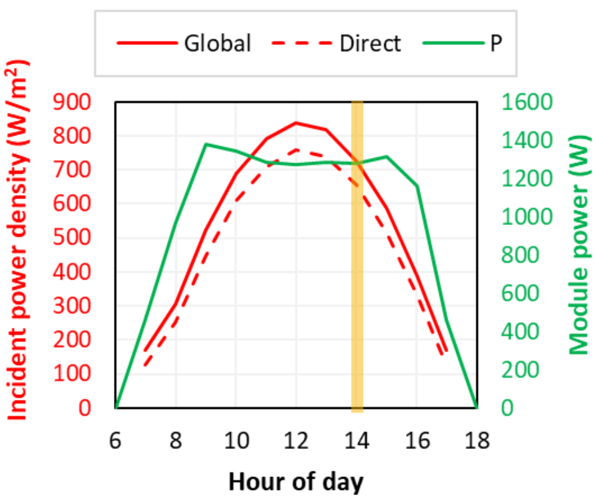

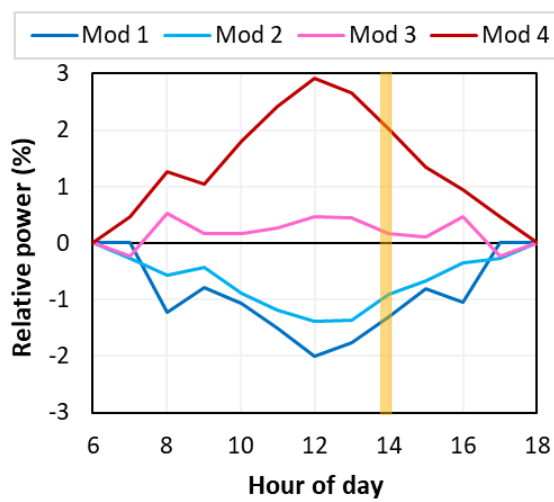

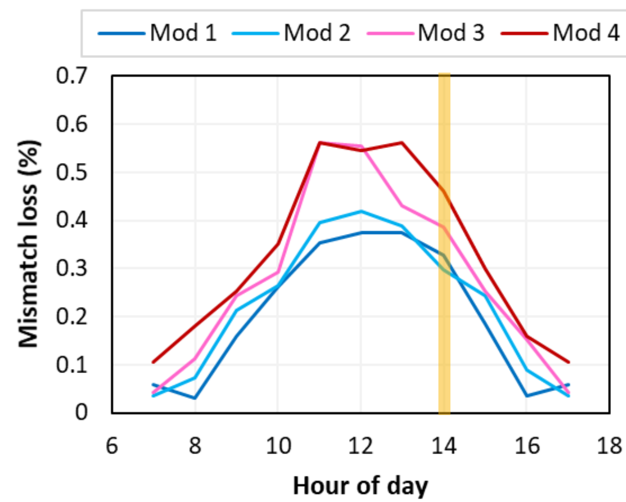

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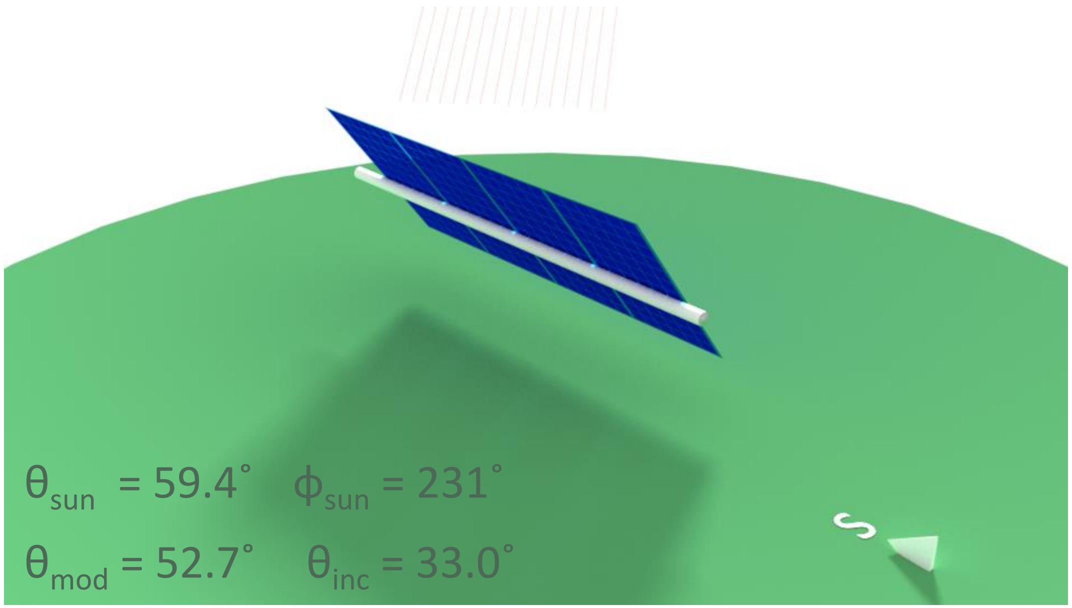

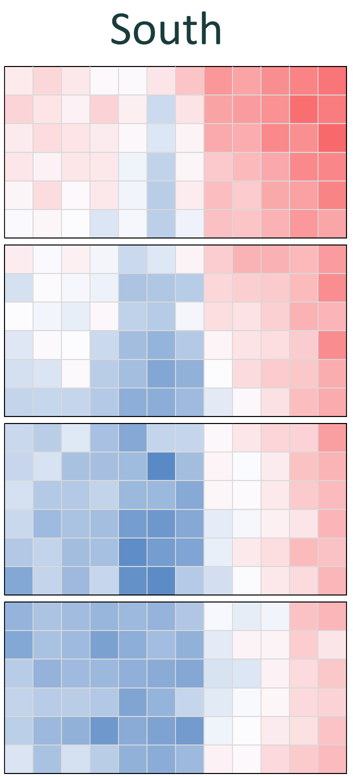

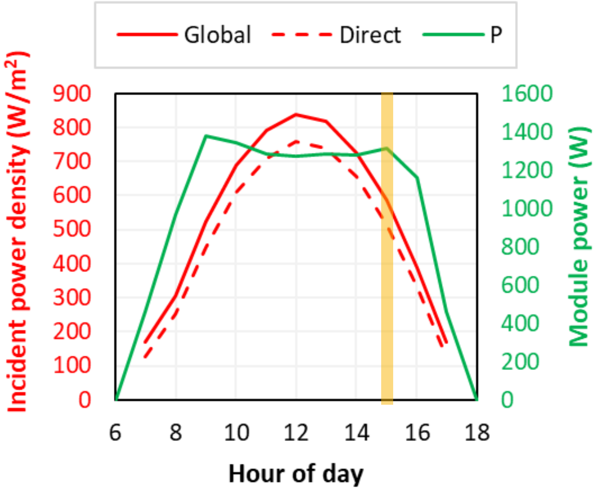

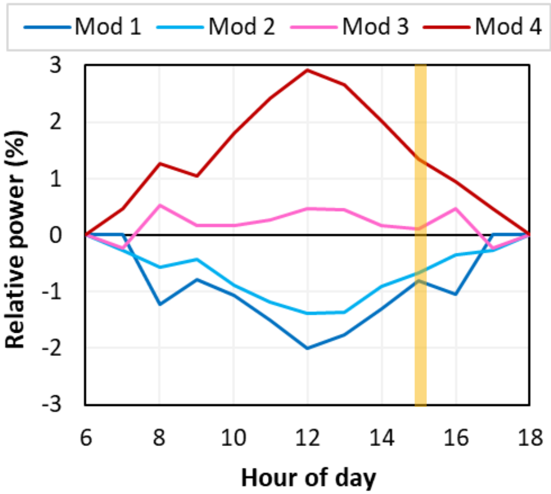

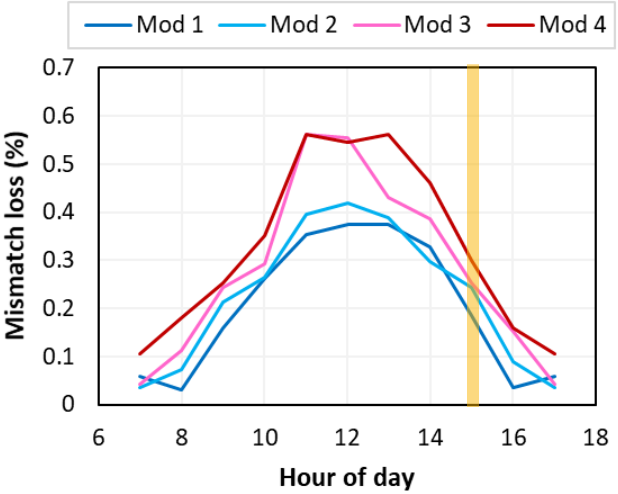

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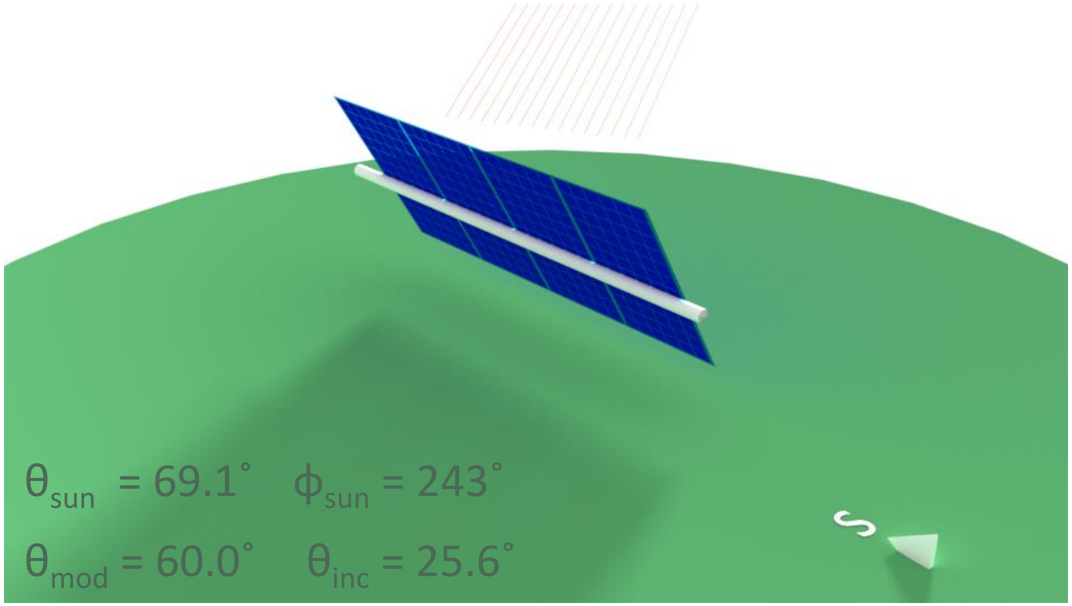

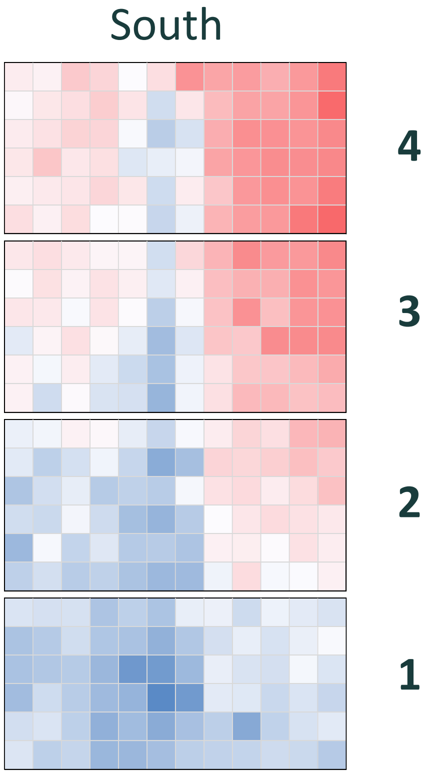

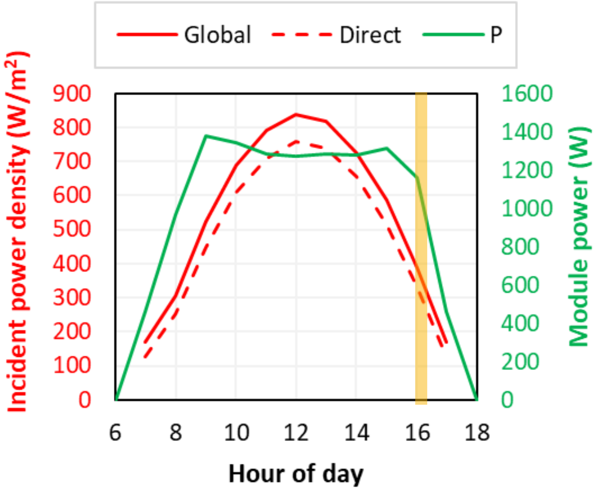

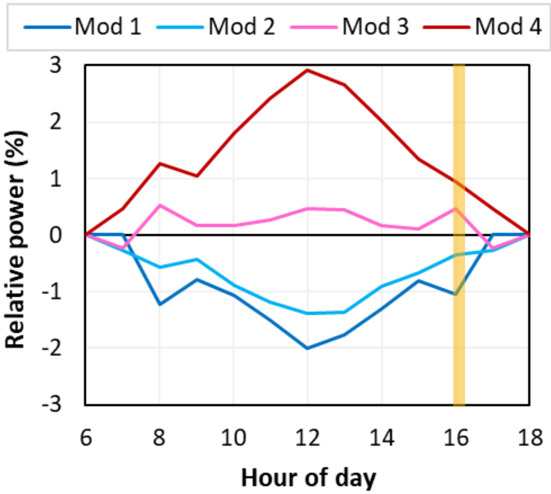

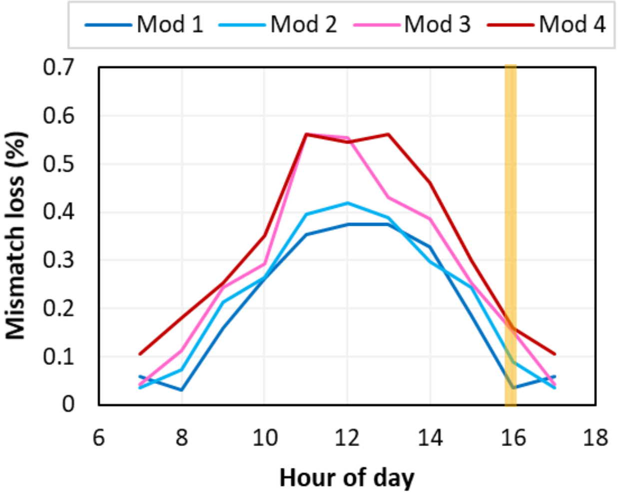

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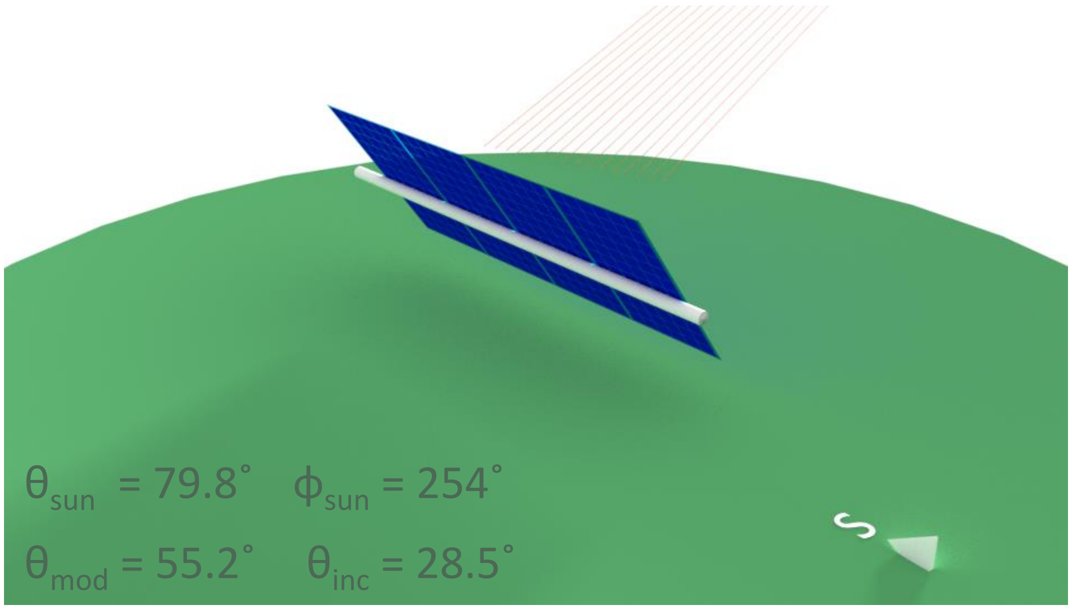

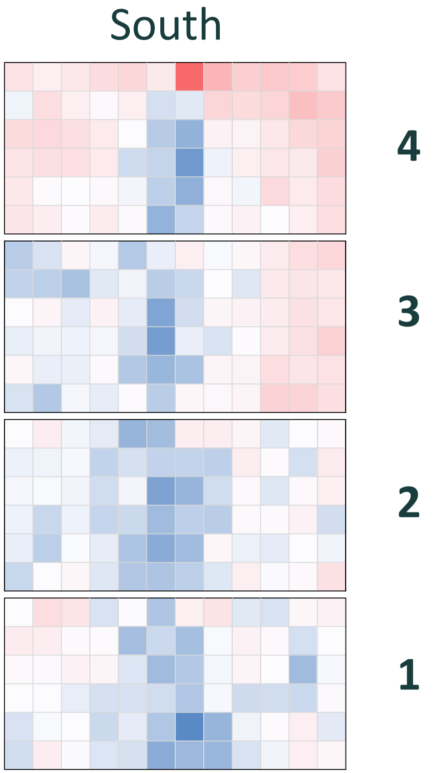

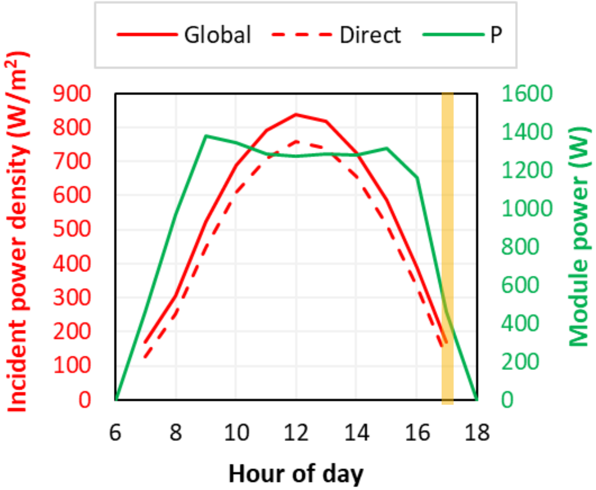

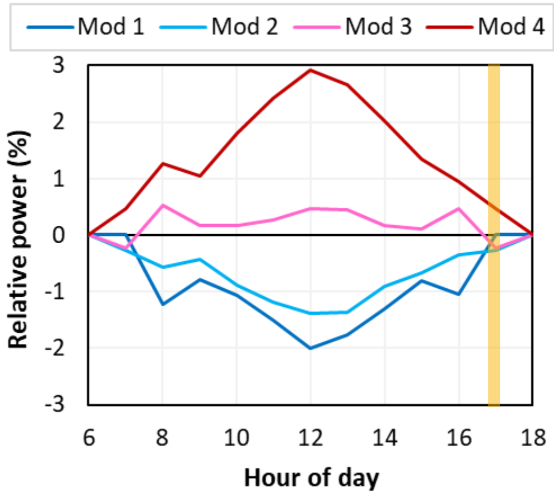

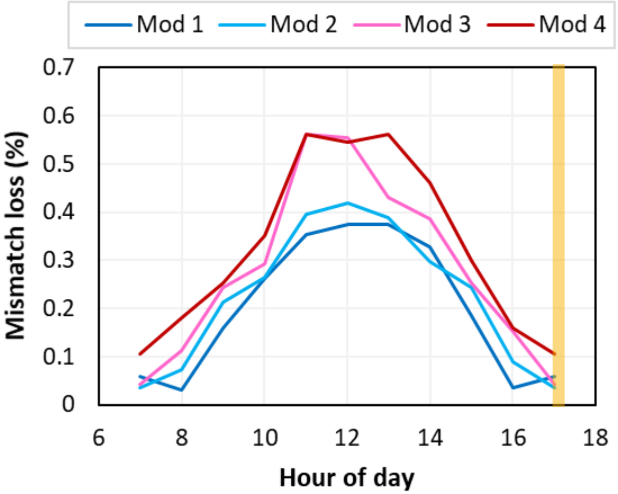

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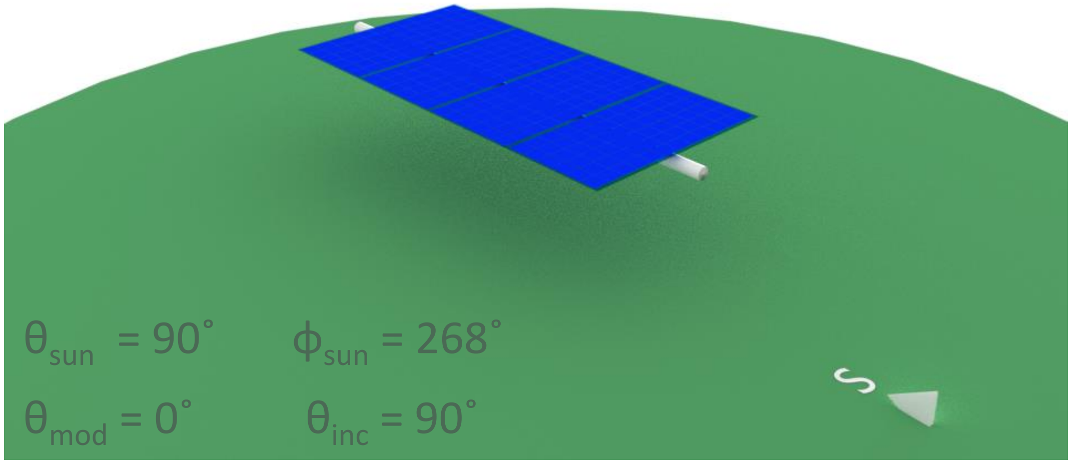
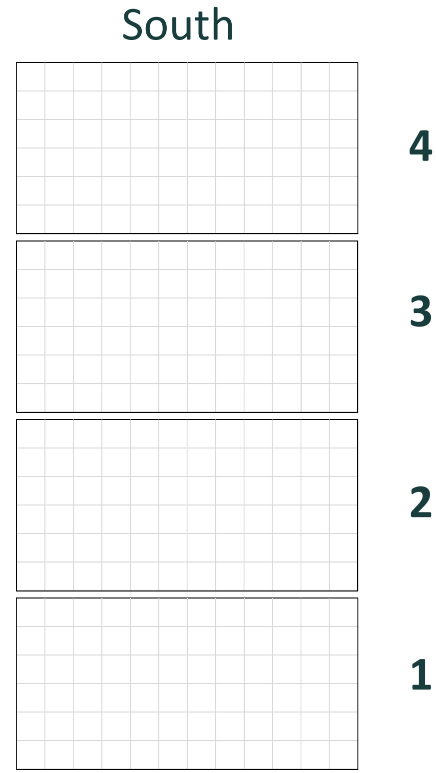
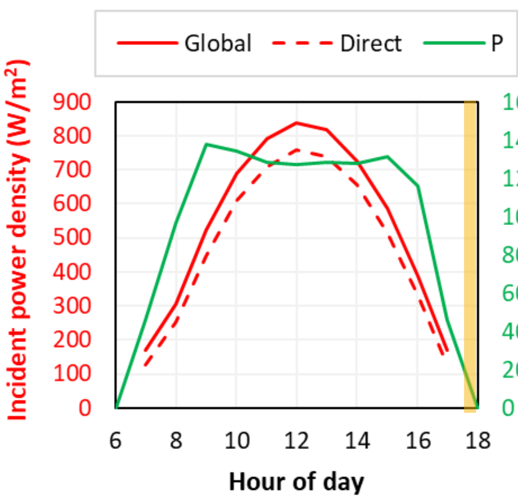
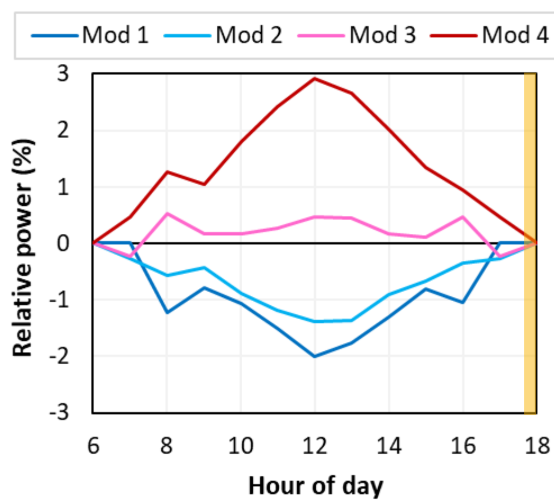
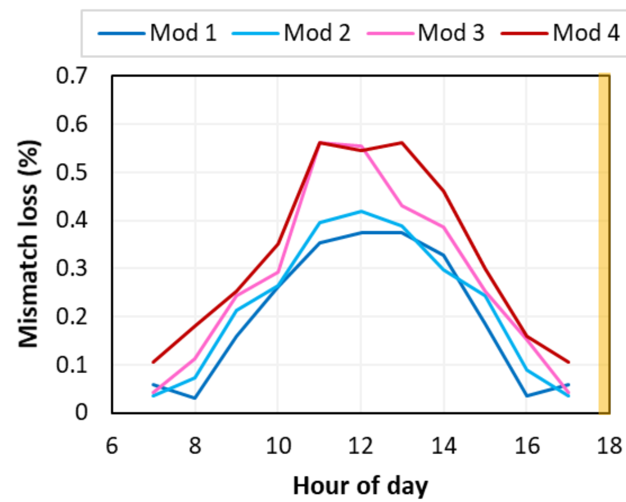




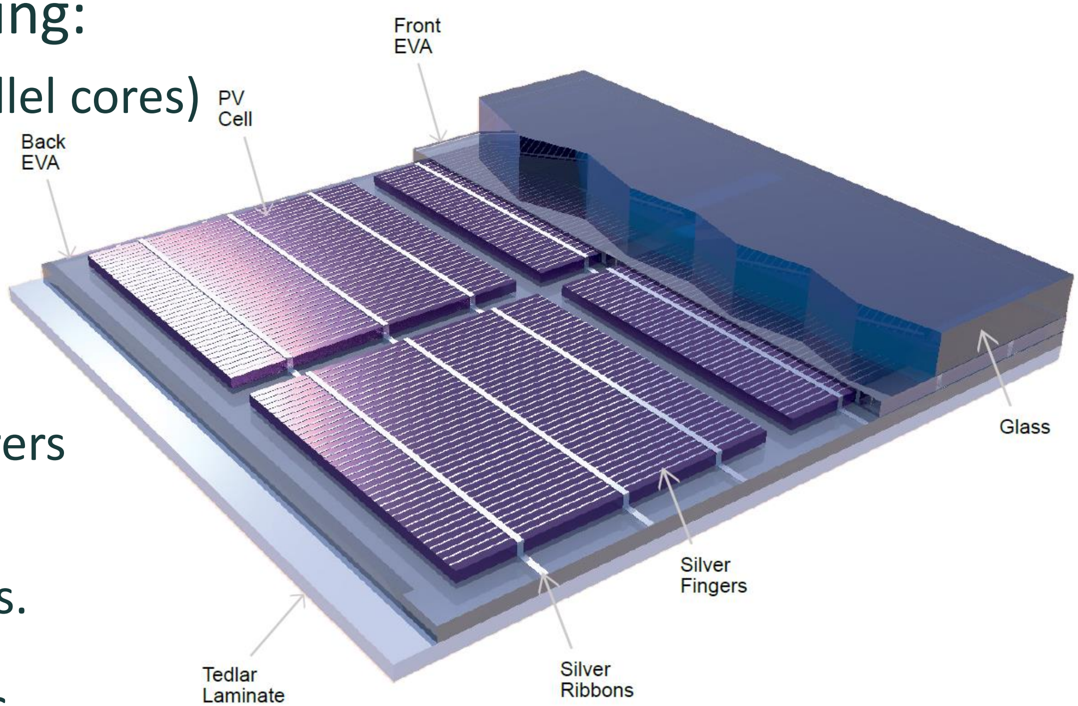






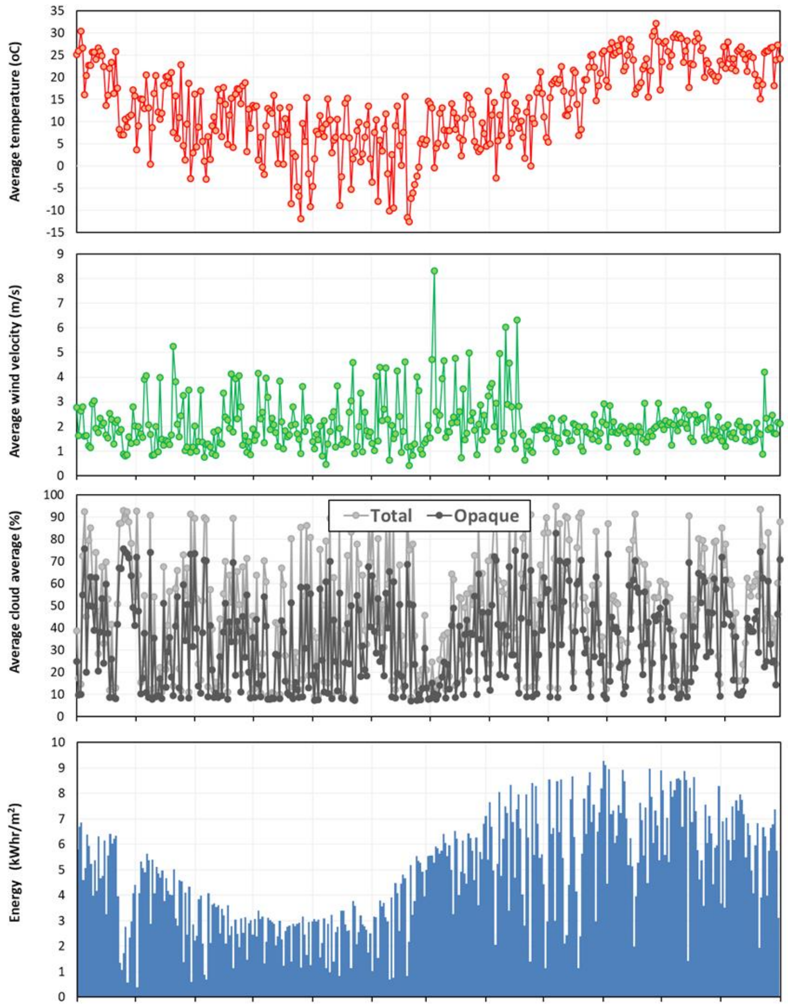
SunSolve™

- Inputs are material properties and geometries.
- Optics solved by ray tracing:
  - cloud-based (≤ 1000 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

12-months at NREL, Colorado



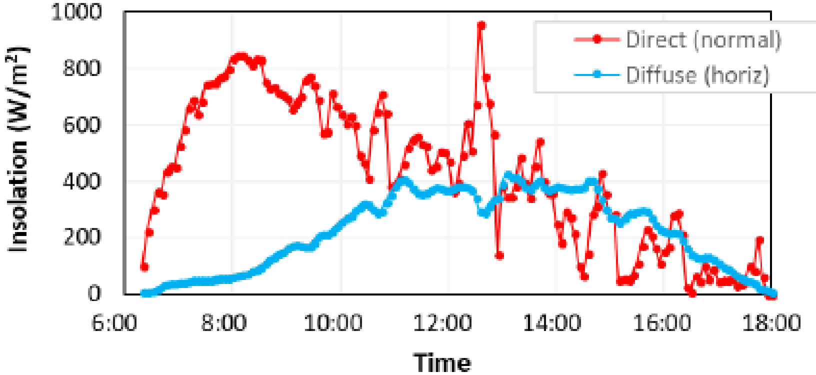
1-Sep-2017

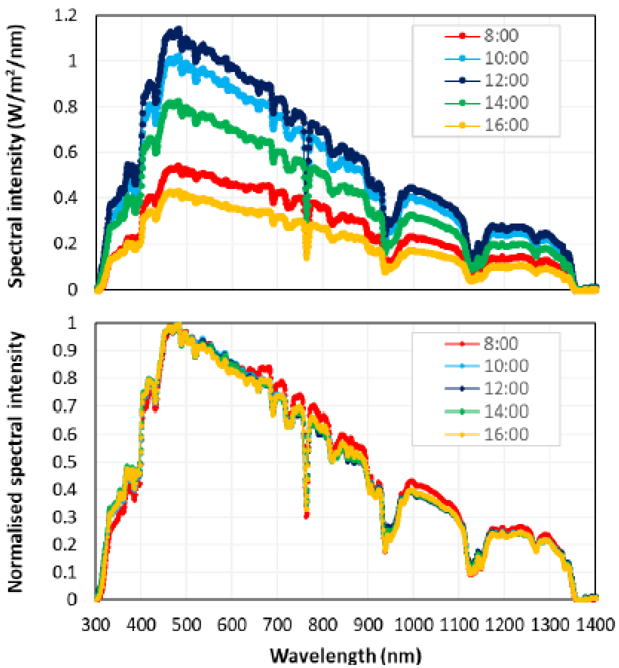
31-Aug-2018

Data from NREL databases

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

12-months at NREL, Colorado





Data from NREL databases for 14-Mar-2018.

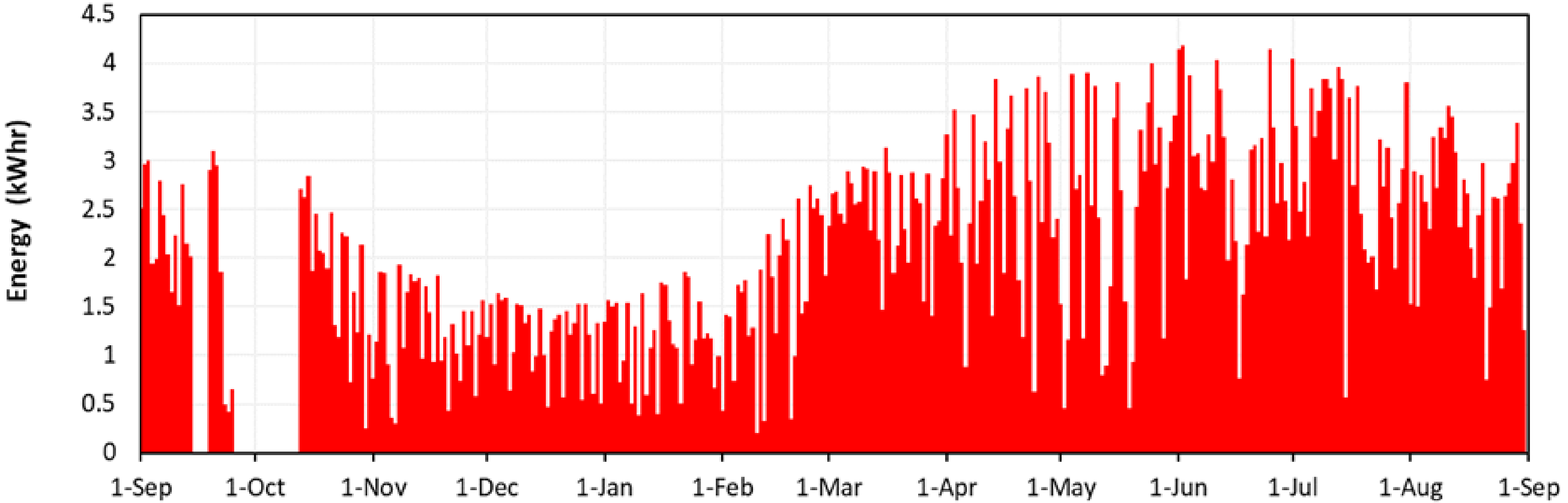
- Integrated direct intensity
- Integrated diffuse intensity

- Global spectra
- Direct spectra

→ Diffuse spectra

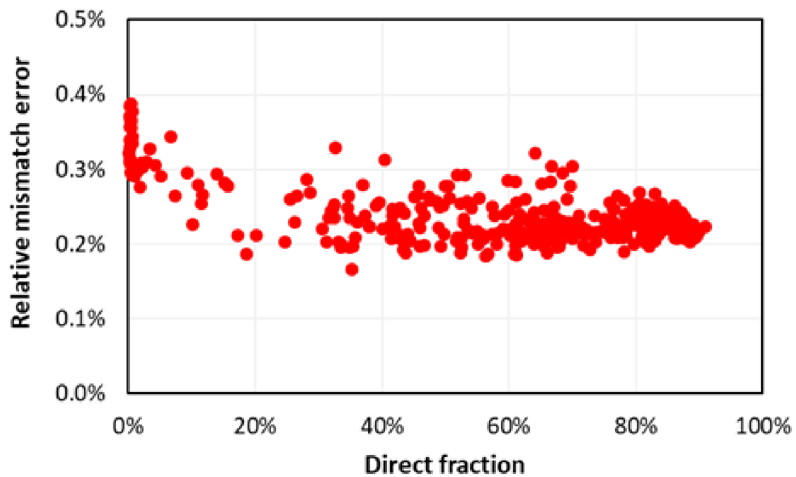
Solving annual yield

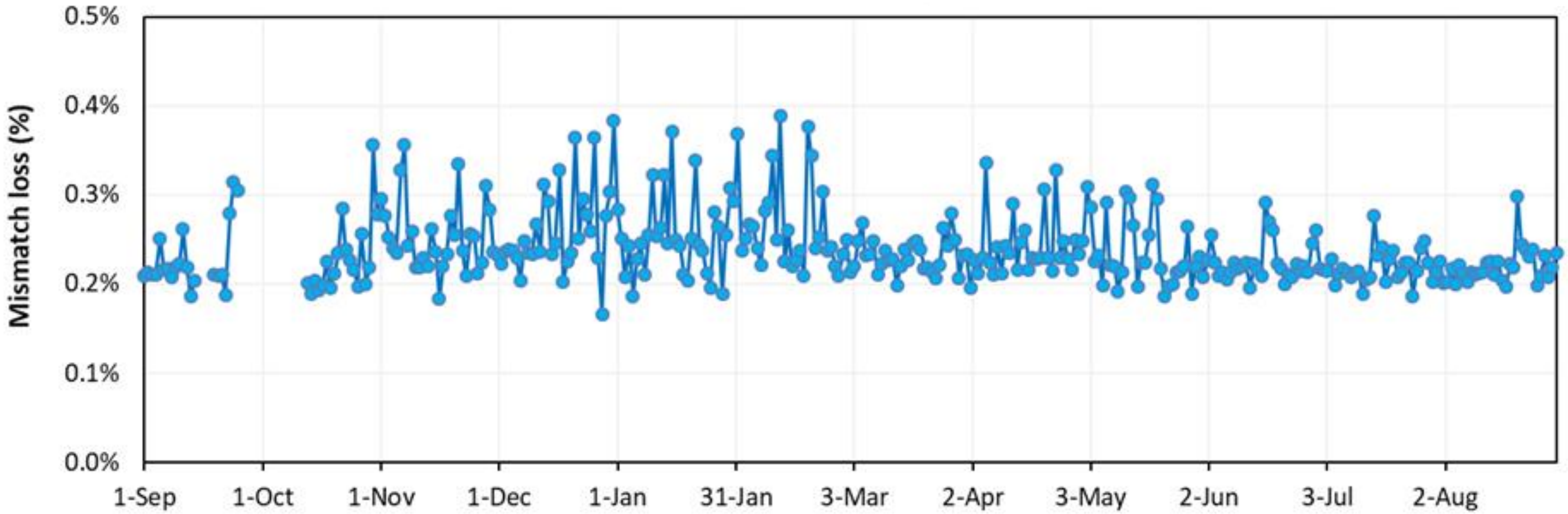
- 20 million rays per incident angle.
- 4400 solutions per year (hourly in daylight hours).
- ~45 mins to solve the annual yield per system configuration (ray tracing + temperature solving + SPICE solving).
- Ways to reduce solutions to <5 mins have been identified.



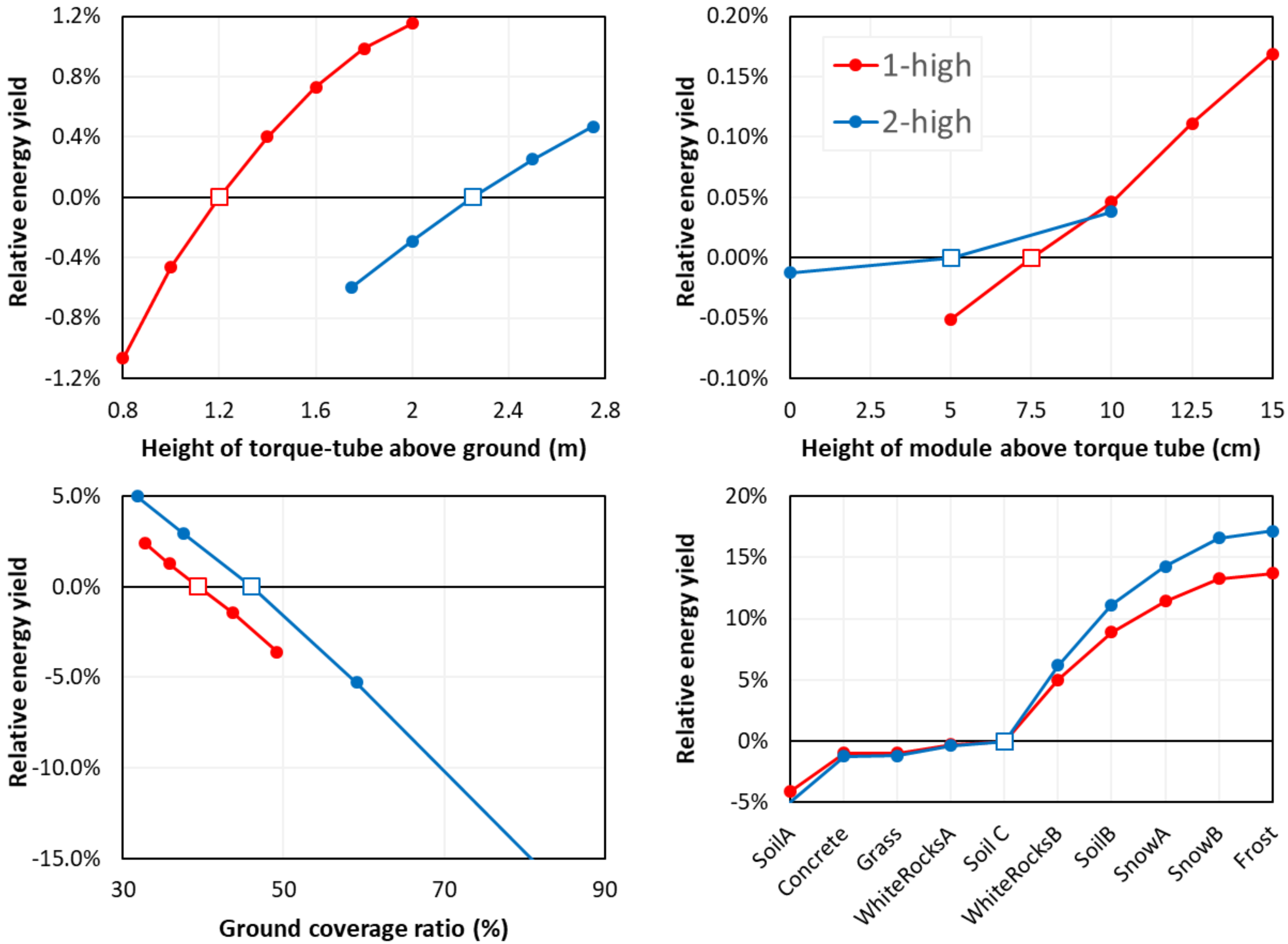
Mismatch loss
(due to non-uniform illumination in module)

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





Evaluate different system configurations



Accuracy of predicting daily yield

- For our location, albedo, module & system configuration, we define accuracy of daily yield prediction.
- Spectral dependencies have the greatest influence.

Global intensity	Non-uniformity in module	T_{amb} & wind	Direct intensity	Spectral dependencies	Uncertainty
✓	✓	✓	✓	✓	0%
✓	✓	✓	✓		±11.4%
✓					±18.4%

Uncertainty to 95% confidence.

Summary

- It can be done:
  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.
- Solutions currently ~45 mins per configuration. Future: < 5mins.
- Results allow us to quantify advantages
  - system configurations,
  - module features,
  - simulation assumptions.
- Is it worth accounting for spectral variability & mismatch due to non-uniformity? Early days, but yes, it looks that way.

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Thank you

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