Differences between advanced and conventional models in bifacial yield simulations

PVPMC Workshop
10-May-2023

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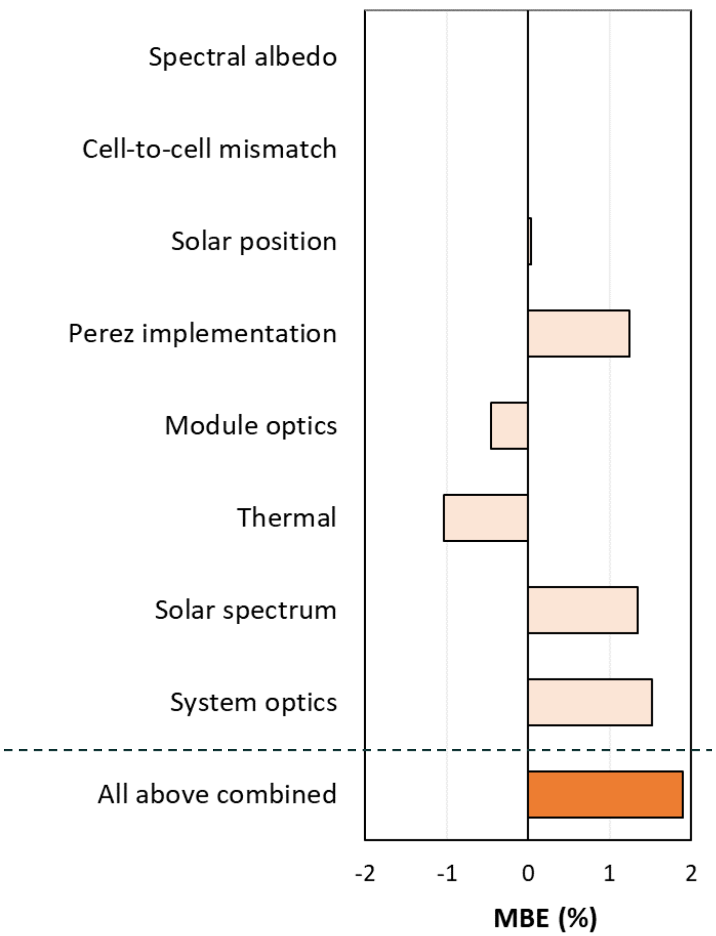
Objective

- Quantify the difference between models for 8 physical mechanisms
  - Mostly tested with SunSolve-Yield
  - And PVSyst for its VF model
- Three system configurations
  - SATs
  - Fixed-tilt
  - Waves
- Just one location
  - Southwest Utah

Results preview

PV LIGHTHOUSE

Results for typical 1P SAT located at Cove Mountain, UT.

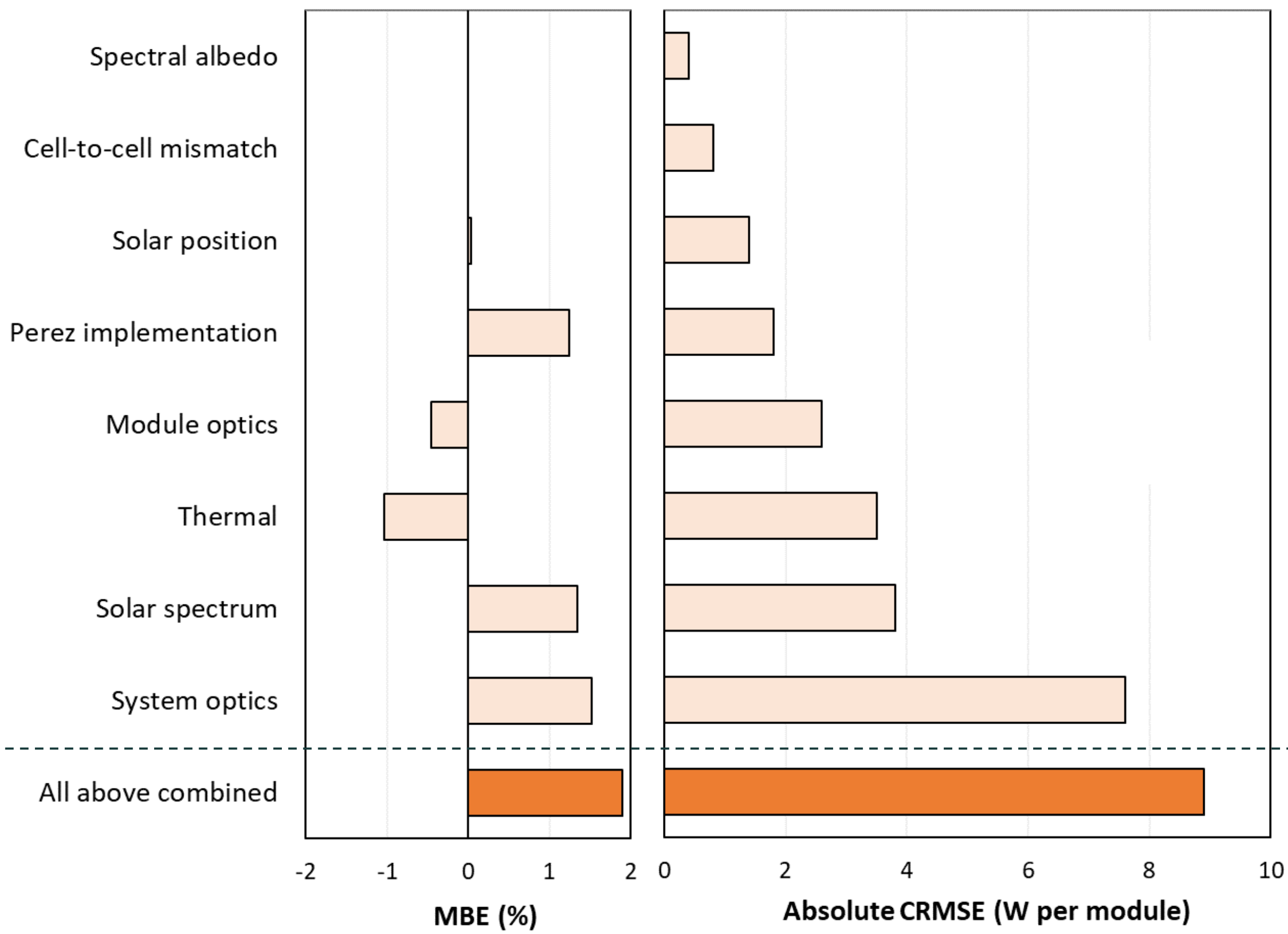


- MBE > 0: yield higher for conventional model than advanced model
- Models are convoluted
  - MBEs of individual models do not sum to MBE of all models combined.
- MBE = 0 does not imply two models are equivalent. Maybe
  - morning discrepancy compensated by noon discrepancy,
  - summer compensated by winter,
  - one poor sub-model compensated by another poor sub-model.

Results preview

LIGHTHOUSE

Results for typical 1P SAT located at Cove Mountain, UT.



Average P_{mod}

315 W

Three early comments

PV LIGHTHOUSE

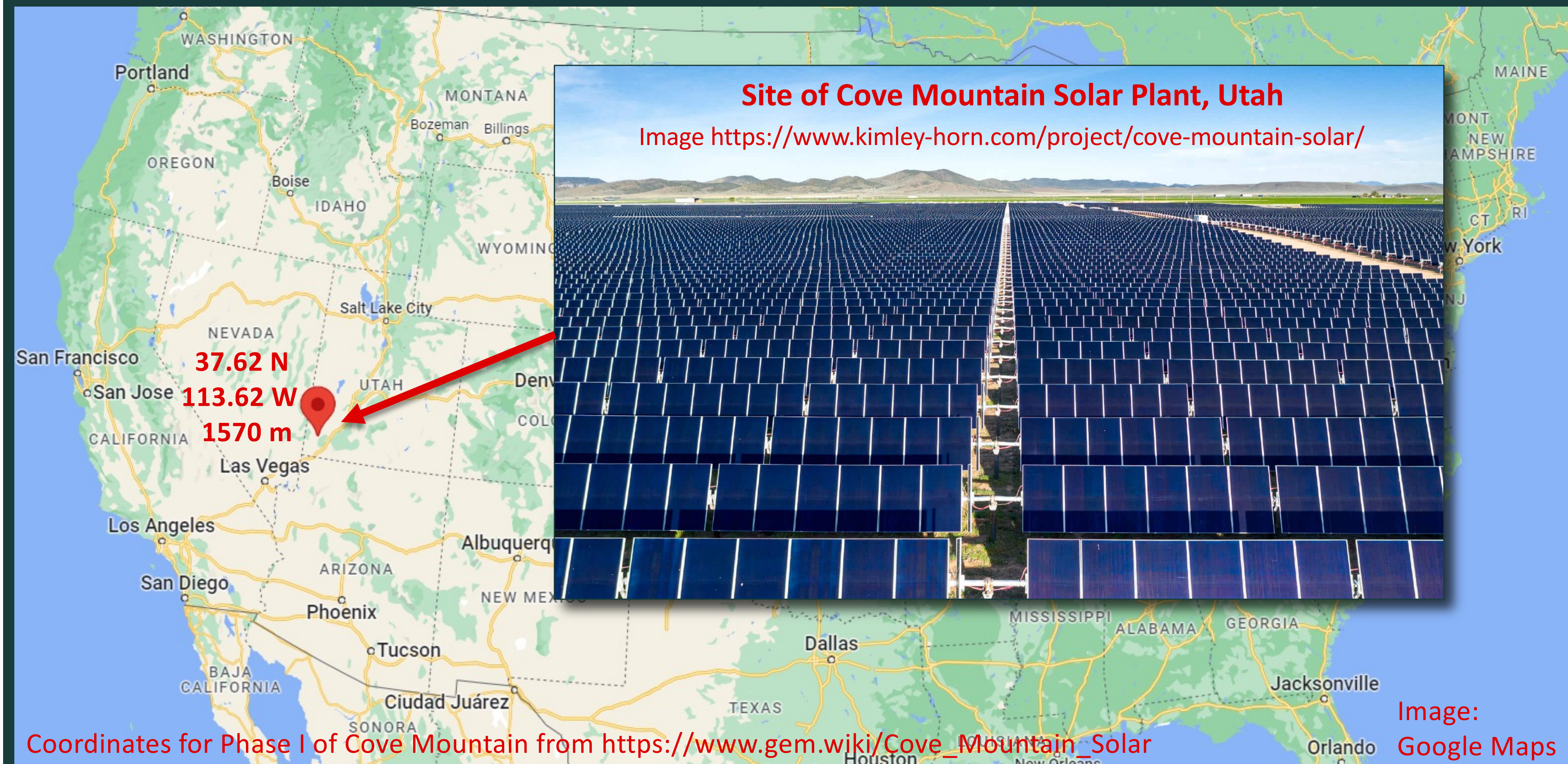
- This is not an investigation into the accuracy of the models.

- Results specific to chosen examples.
  - Model comparisons will differ for other location, weather, system configurations.
  - Consider these results as a general guide, with more emphasis on CRMSE than MBE.

- By themselves, these results don't promote any model over another. The value of a model depends on many things:
  - Accuracy, precision, uncertainty
  - Ease of implementation & determining inputs
  - Acceptance by industry
  - Modelling objective: e.g., annual yield, morning power, structural shading, etc.

Simulation details

Simulation details — site location



37.62 N
113.62 W
1570 m

Site of Cove Mountain Solar Plant, Utah

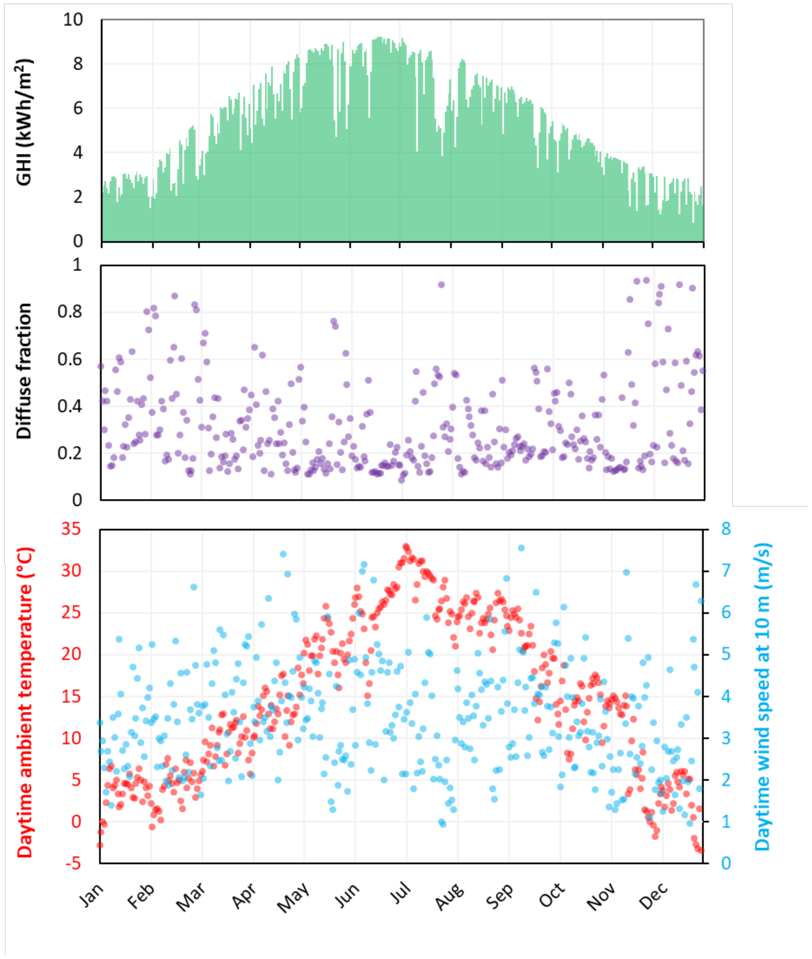
Image https://www.kimley-horn.com/project/cove-mountain-solar/

Coordinates for Phase I of Cove Mountain from https://www.gem.wiki/Cove_Mountain_Solar

Image: Google Maps

Simulation details — weather

- Good solar resource
- Low cloud
- Cold winter, warm summer
- Mostly light winds



$I = 1.96\ MWh/m^2$

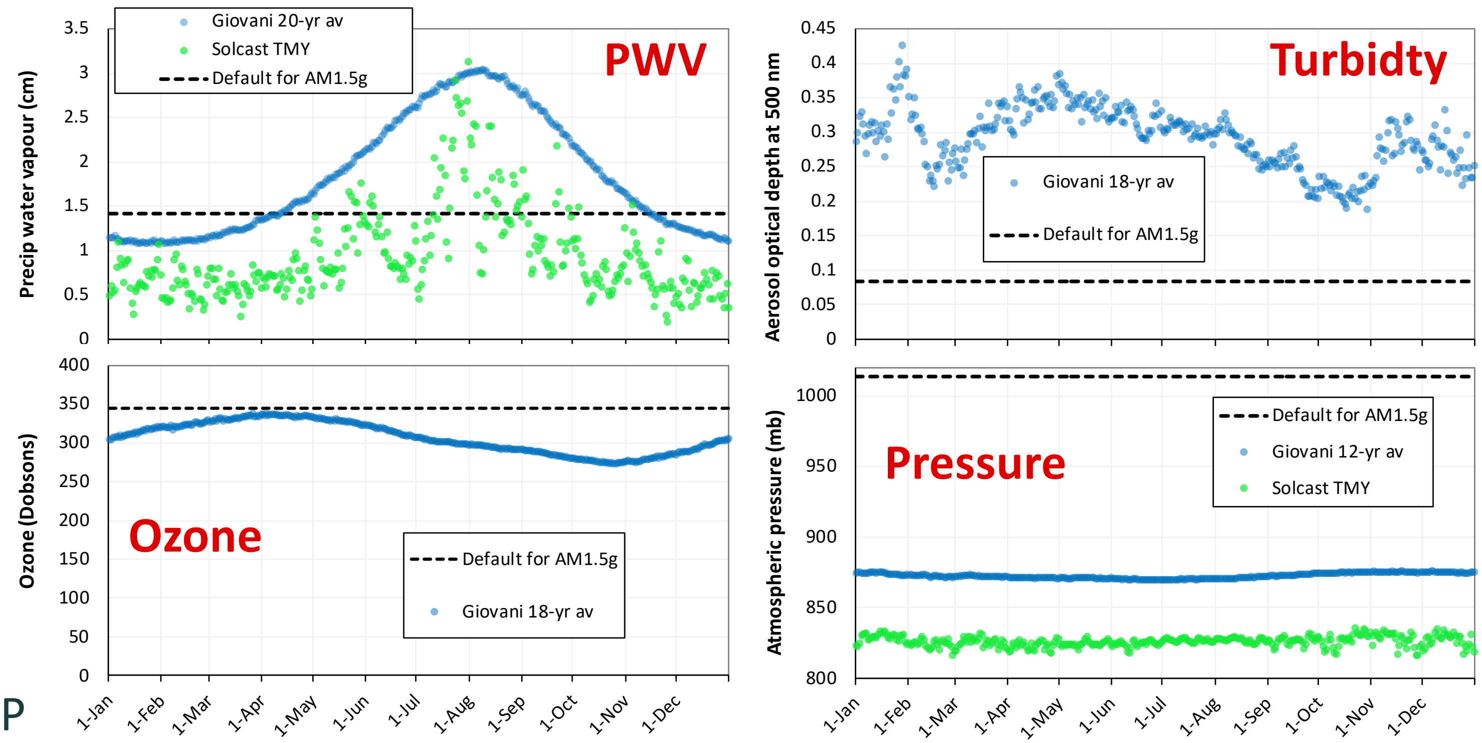
$f_D = 26.5\%$

$T_{av} = 14.7\ ^oC$

$w_{av} = 3.5\ m/s$

Simulation details — atmosphere

- Relatively dry
- Dusty
- Moderate ozone
- Low pressure due to altitude (1570 m)



- We use
  - Solcast for PWV & P
  - Giovani for O_3 and turbidity

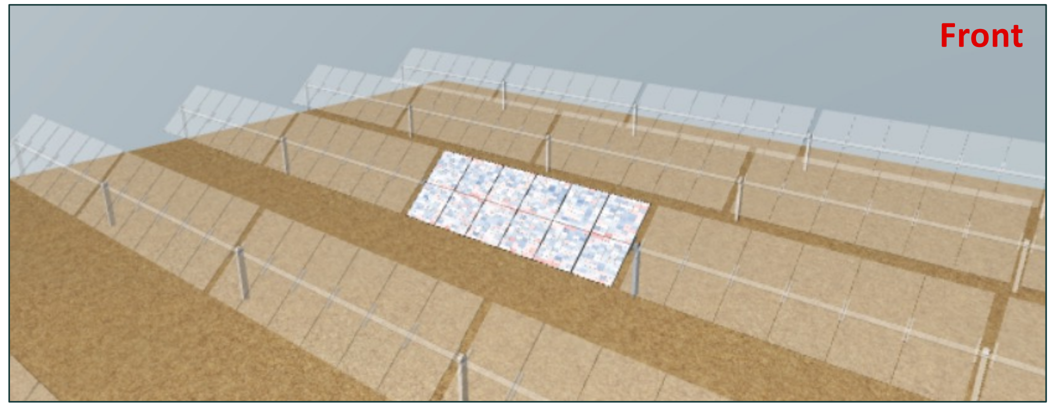
Blue data is long-term daily average from NASA's satellites and analysis of 1^o bounding box. https://giovanni.gsfc.nasa.gov/giovanni.

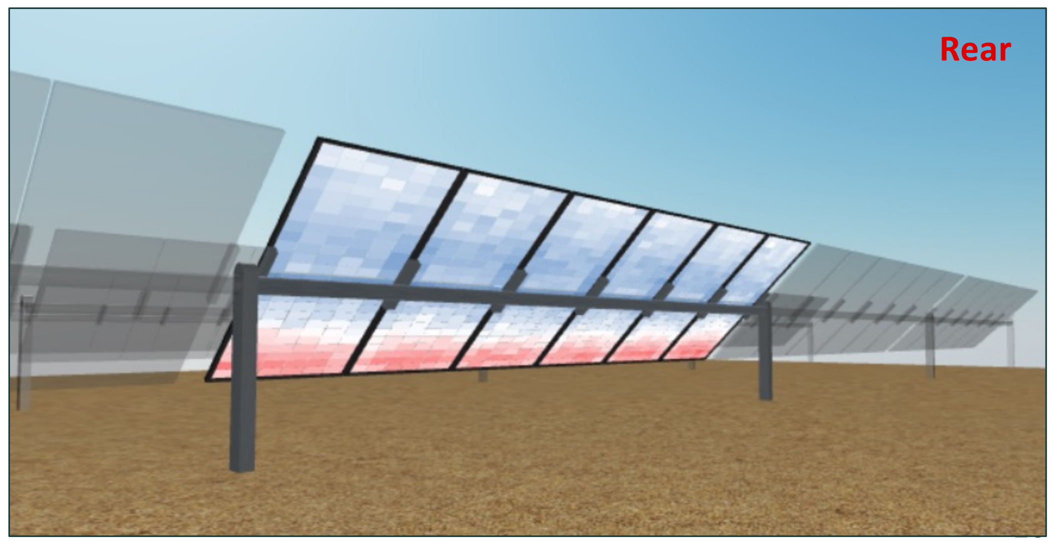
Green data is daily average of Solcast, recently acquired by DNV. https://solcast.com/

Simulation details — SAT

- 1P (one in portrait)
- Six modules per bay
- Posts between bays
- Circular torque tube
- Small clamps (rails)
- Max tilt ±55°, backtracking

- Example results of ray tracing for 9 am, 10-May, light cloud.

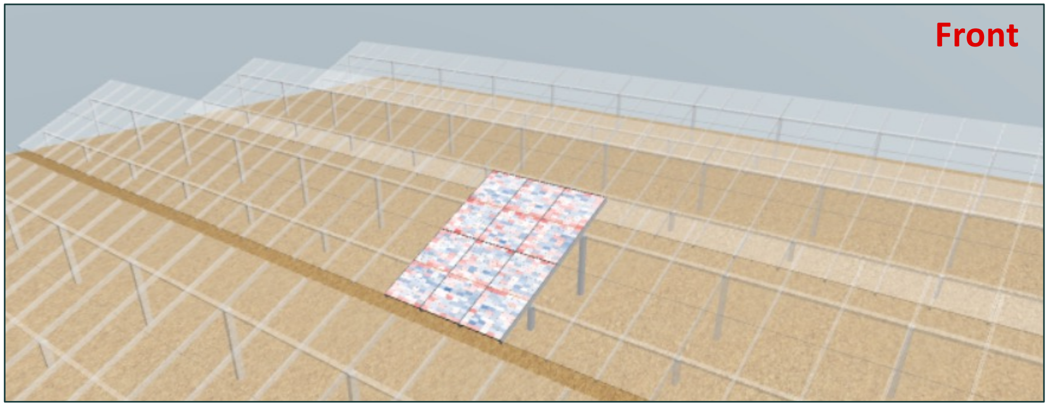


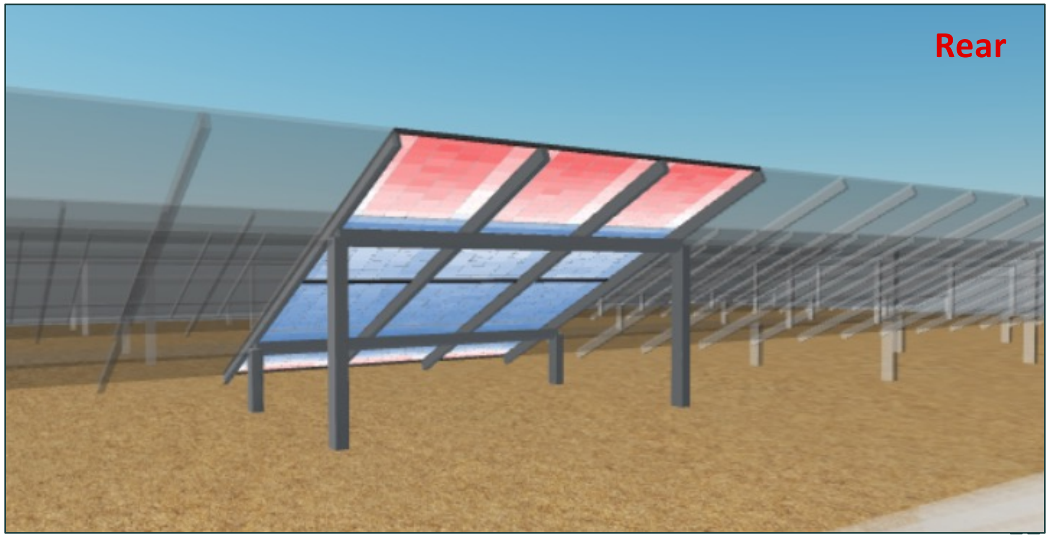


Simulation details — fixed-tilt

- 2P (two in portrait).
- Six modules per bay
- Posts between bays
- Rafters
- Purlins
- Tilt 25°

- Example results of ray tracing for 10 am, 10-May, light cloud.

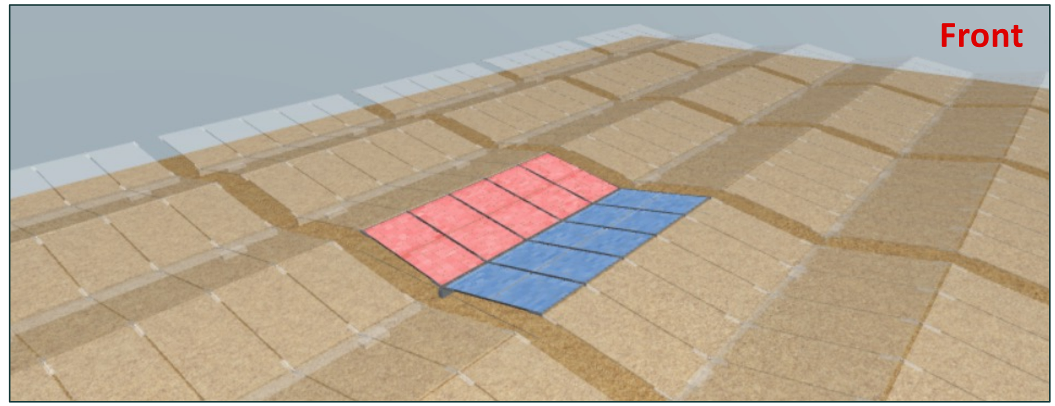


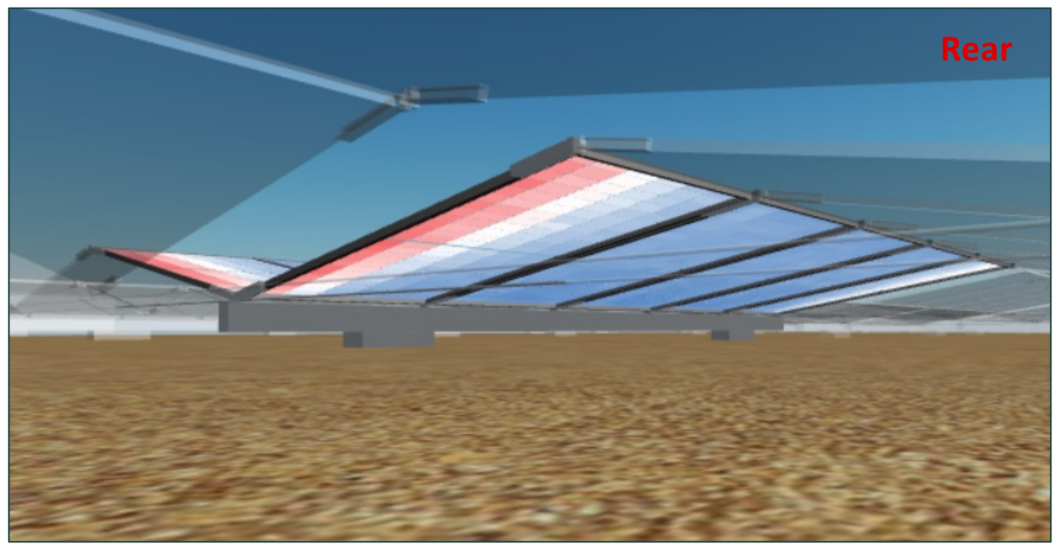


Simulation details — waves

- 1P (one in portrait).
- Ten modules per wave.
- Concrete slabs below modules.
- Rafters
- Purlins
- Tilt 10º.

- Example results of ray tracing for 9 am, 10-May, light cloud





Simulation details — module

PV LIGHTHOUSE

P_{MP}	550 W	V_{OC}	49.80 V	V_{MP}	41.95 V	FF:	0.790
Bifi	70%	I_{SC}	13.99 A	I_{MP}	13.12 A	Eff:	21.31%

LONGI LR5-72HBD 550M

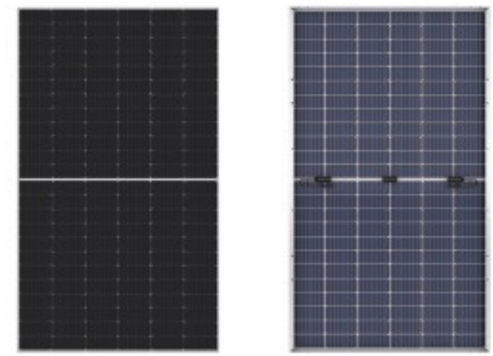
144 half-cut cells

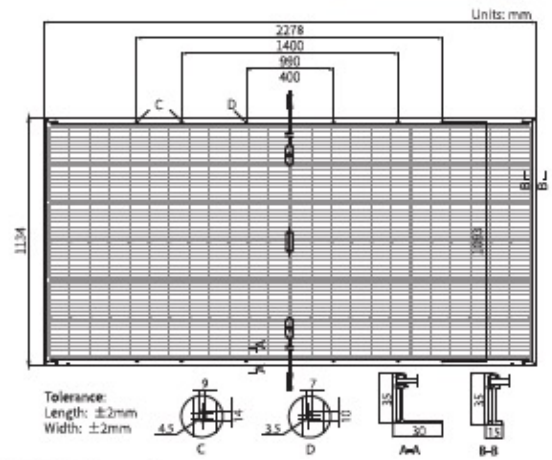
Temperature Ratings (STC)

Temperature Coefficient of Isc	+0.050%/°C
Temperature Coefficient of Voc	-0.265%/°C
Temperature Coefficient of Pmax	-0.340%/°C

Mechanical Parameters

Cell Orientation	144 (6×24)
Junction Box	IP68, three diodes
Output Cable	4mm², +400, -200mm/±1400mm length can be customized
Glass	Dual glass, 2.0+2.0mm heat strengthened glass
Frame	Anodized aluminum alloy frame
Weight	32.6kg
Dimension	2278×1134×35mm
Packaging	31pcs per pallet / 155pcs per 20' GP / 620pcs per 40' HC





Simulation details — general

- Infinitely large system — no edge effects from system perimeter.
- DC module output — average of all modules in a bay.
- 1 hourly time steps.

Models examined

1. Spectral albedo

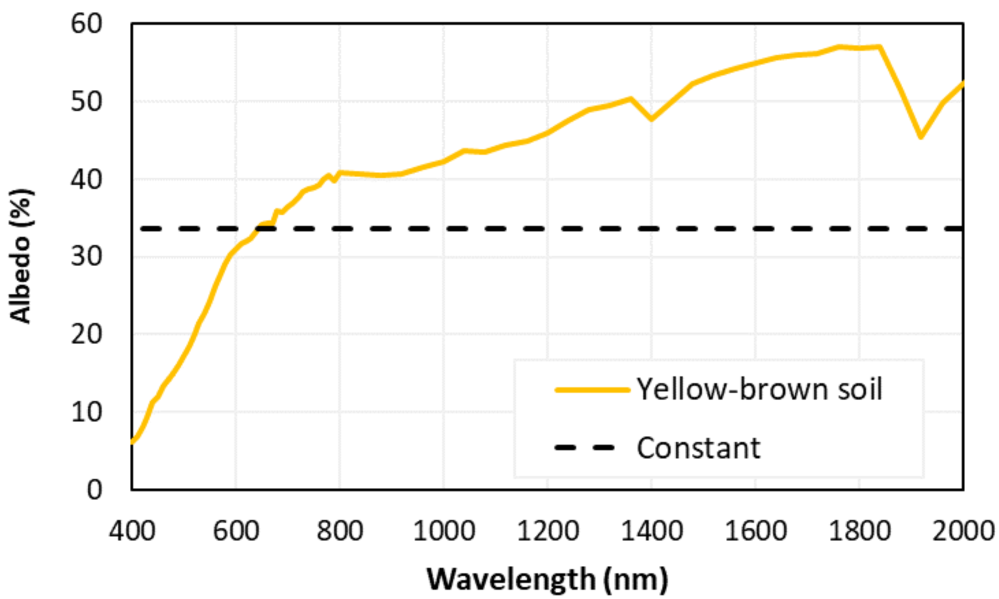
PV LIGHTHOUSE

Conventional

- Constant
- 33.7%

Advanced

- Wavelength-dependent
- Yellow-brown soil (NASA)



2. Electrical mismatch

Conventional

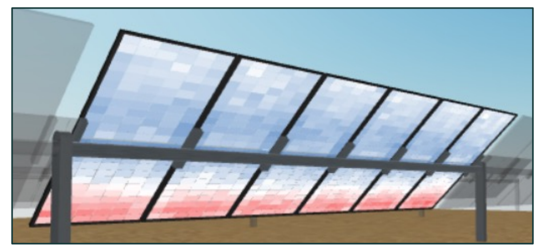
- Constant
  - Here, we use the annual weighted average mismatch loss f_M as determined by SunSolve (front & rear combined)

	f_M
SAT	0.5%
Fixed	0.5%
Waves	0.7%

Fixed f_M omits row-to-row shading of direct light since that is accounted for in PVSyst.

Advanced

- Calculated at all time steps
  1. Solve J_L in each cell



  2. Solve equivalent-circuit of module

3. Solar position

LIGHTHOUSE

<u>Conventional</u>

- PVSyst [1]
  - Simple equations.
  - Omits refraction.

<u>Advanced</u>

- Reda–Andreas 2004 [2]
  - Masses of tables and equations.
  - Accounts for refraction.
  - Zenith and azimuth to within ±0.0003° between 2000 BCE and 6000 CE.

[1] https://www.pvsyst.com/help/solar_geometry.htm

[2] Reda and Andreas, “Solar position algorithm for solar radiation applications,” *Solar Energy* **76** (5), 577–589, 2004.

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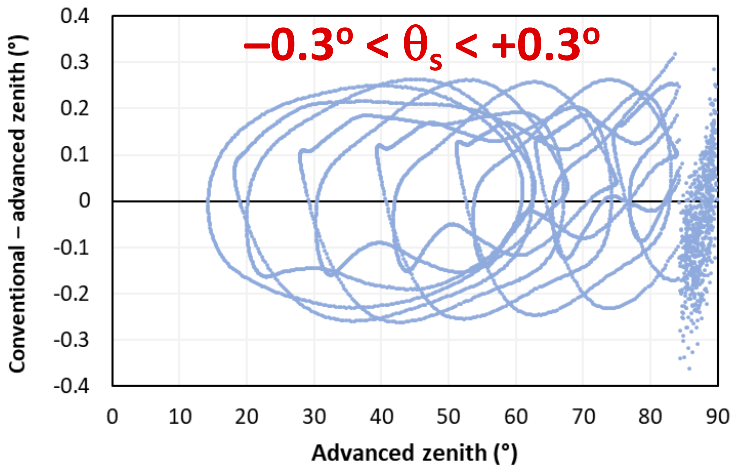
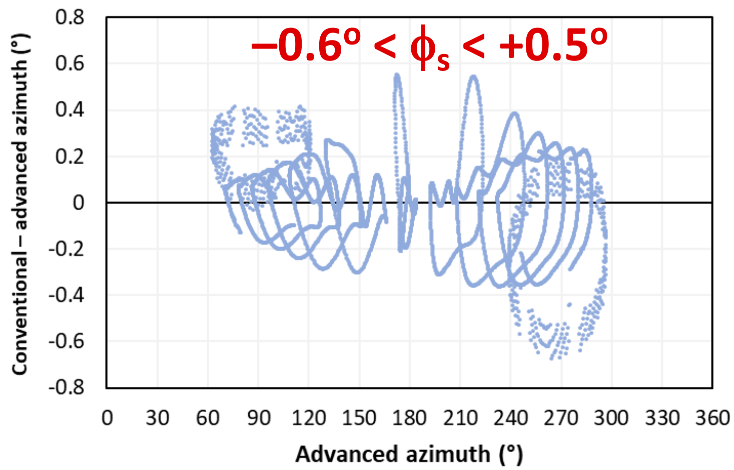




4. Diffuse sky distribution

PV LIGHTHOUSE

Conventional

- PVSyst Perez (1990) [7]

Alternative implementation

- PVL Perez (1990)

NB: Change in yield when using Hay–Davies [8] rather than Perez in our example:

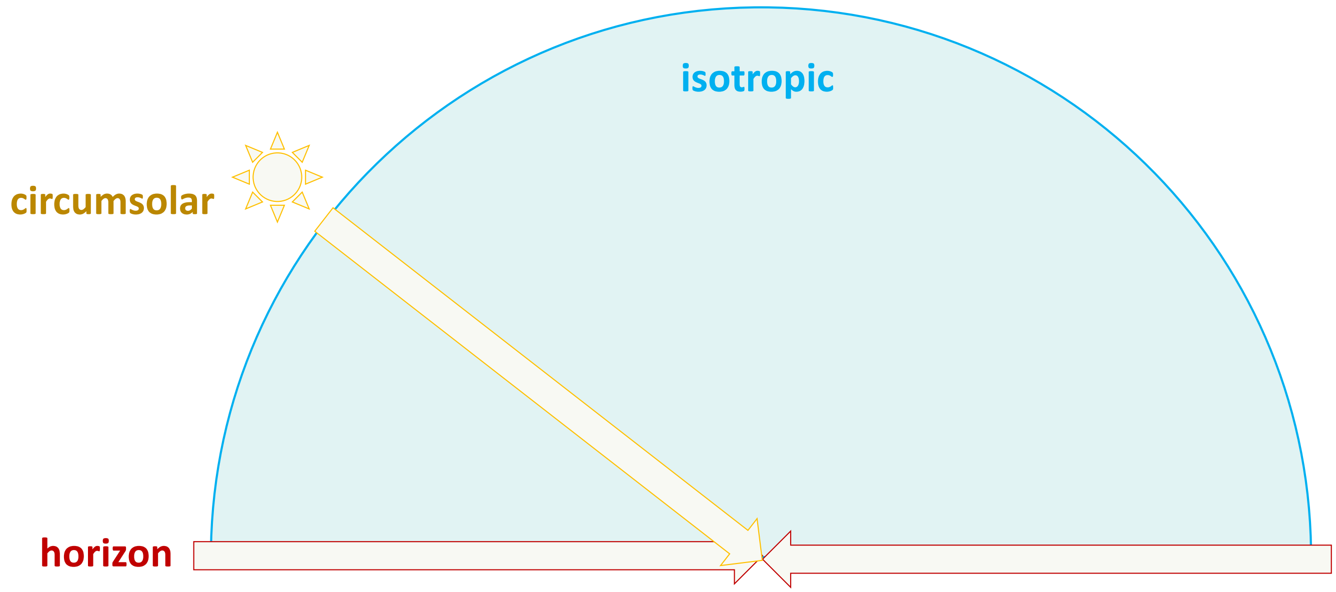
	Conventional (PVSyst)	**Alternative (SunSolve-Yield)**
SAT	-1.35%	+0.15%
Fixed	-1.50%	+0.17%
Waves	-0.65%	+0.80%

[7] Perez et al., "Modeling daylight availability and irradiance components from direct and global irradiance," *Solar energy* **44** (5),.271-289, 1990.
[8] Hay and Davies, "Calculation of solar radiation incident on an included surface," *1st Canadian Solar Radiation Data Workshop*, Ontario, 166, 1980.

4. Diffuse sky distribution

Models, like simple Perez (1990),
approximate the diffuse light with three sources:

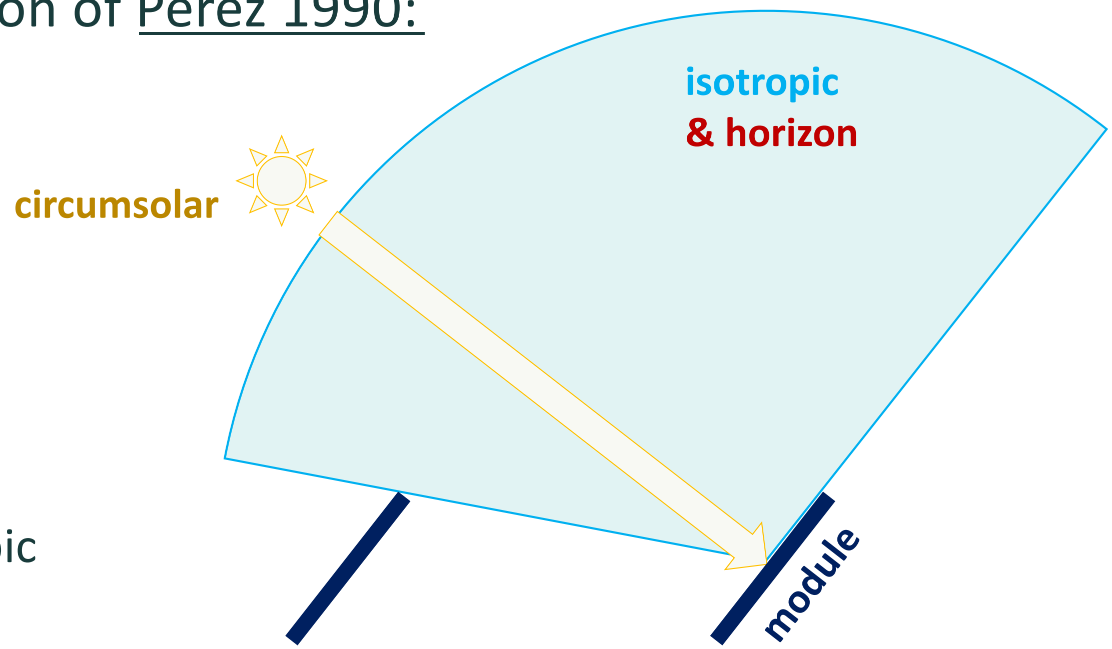
- isotropic
- circumsolar
- horizon



4. Diffuse sky distribution

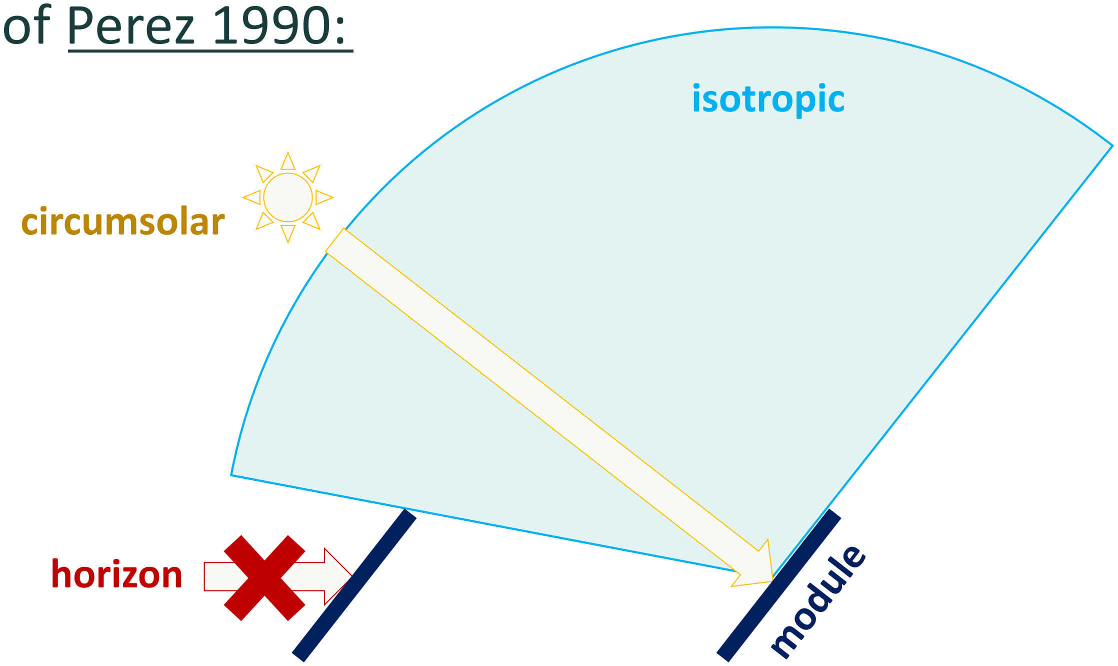
PV LIGHTHOUSE

- Adaption for infinite field accounts for shading from modules.
- PVSyst's implementation of Perez 1990:
- isotropic
  - partial shading
- circumsolar
  - possible shading
- horizon
  - same shading as isotropic



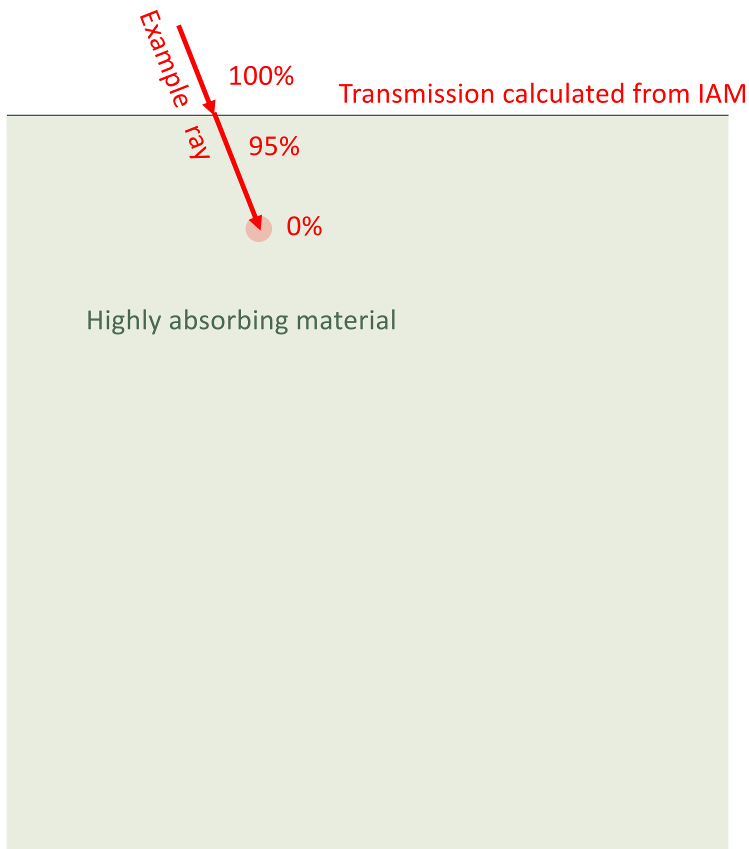
4. Diffuse sky distribution

- Adaption for infinite field accounts for shading from modules.
- PVL's implementation of Perez 1990:
- isotropic
  - partial shading
- circumsolar
  - possible shading
- horizon
  - completely shaded

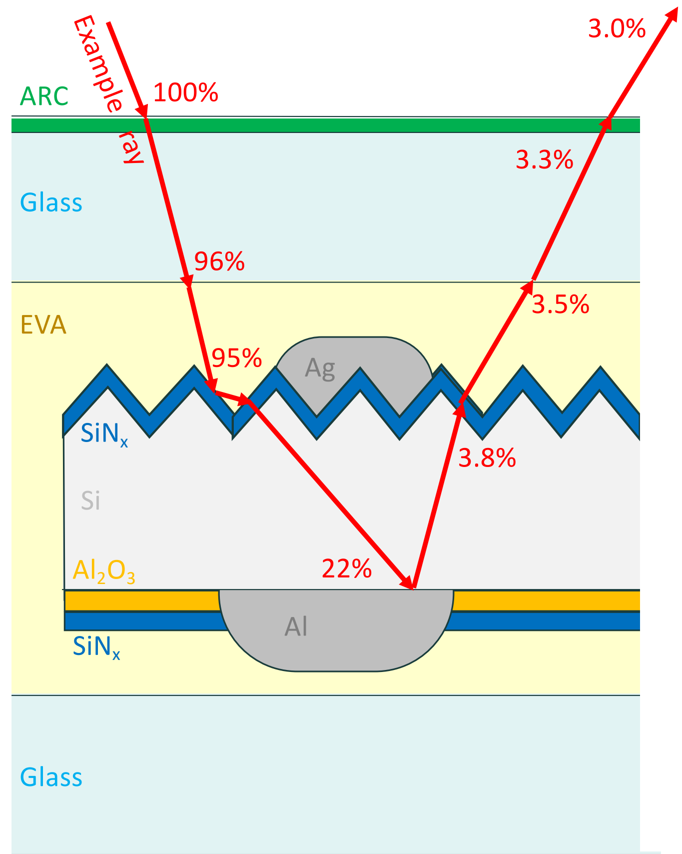


5. Module optics

Conventional



Advanced

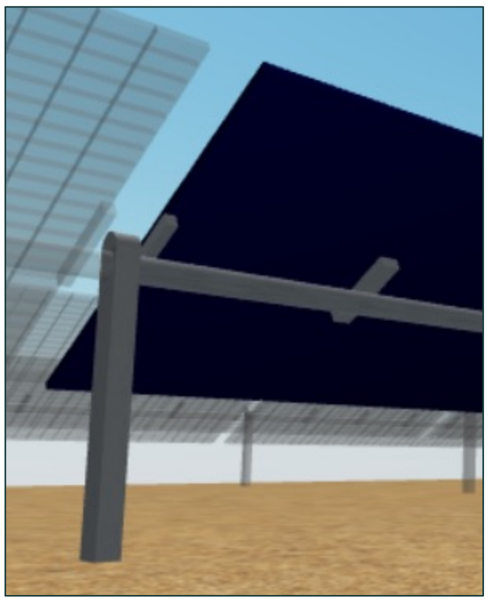


5. Module optics

PV LIGHTHOUSE

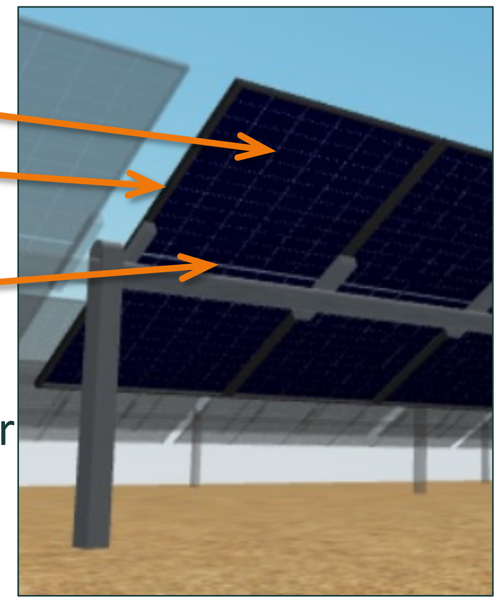
Conventional

- 'Simple' (like PV Syst, SAM, etc.)
  - No reflection
  - IAM from look-up table
  - λ-independent
  - No cell spacing
  - No frames
  - Spatially uniform
  - J_L responds linearly to absorption



Advanced

- Ray tracing into the module
  - Reflection
  - Calcs with Fresnel & thin-film optics
  - λ-dependent
  - Cell layout
  - Frames
  - Fingers, ribbons, backsheet, pyramids, etc.
  - J_L responds linear to absorption

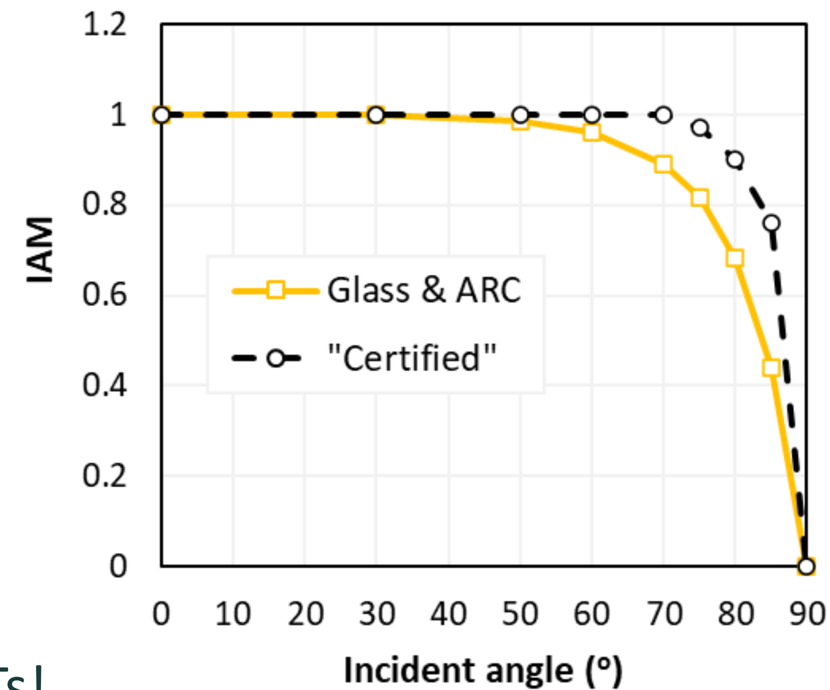


5. Module optics

PV LIGHTHOUSE

Conventional – IAM

- PAN files sometimes contain an unrealistic IAM.
- Sometimes it's even "certified".
- PVSyst allows a calculated IAM instead of PAN IAM
- For conventional, we use calculated IAM, "Fresnel, AR coating"
- "Certified" gives 1.45% more yield for SATs!



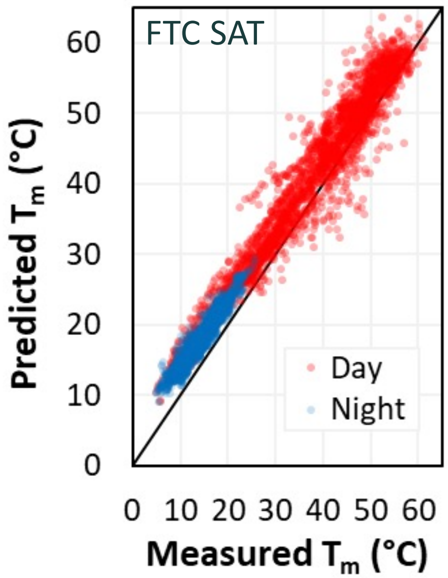
6. Thermal model

Conventional

- Faiman [3]

	U_C	U_V
SAT	25	1.2
Fixed	25	1.2
Waves	27	0

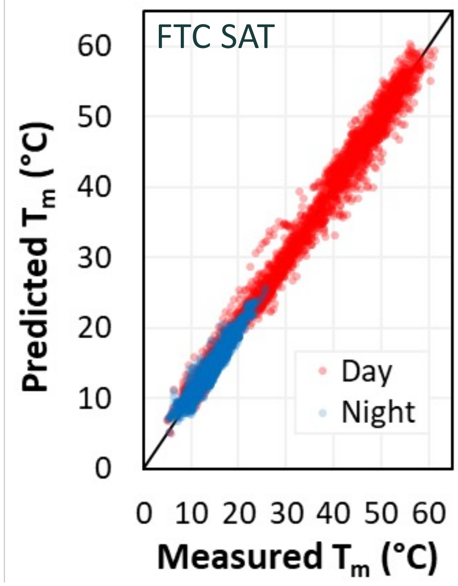
MBE: +3.2 °C
RMSE: 4.5 °C



Advanced

- PVL (PVSC 2022) [4] distinguishes
  - Radiative losses
  - Transient effects
  - Tilt dependence
- Inputs fit to experiment

MBE: 0 °C
RMSE: 1.4 °C



[3] D. Faiman, "Assessing the outdoor operating temperature of photovoltaic modules," *Progress in Photovoltaics*, **16** (4), 307-315, 2008.
[4] K.R. McIntosh *et al.*, "The influence of wind and module tilt on the operating temperature of single-axis trackers," *49th IEEE PVSC*, 1033-1036, 2022.

7. Solar spectra

Conventional

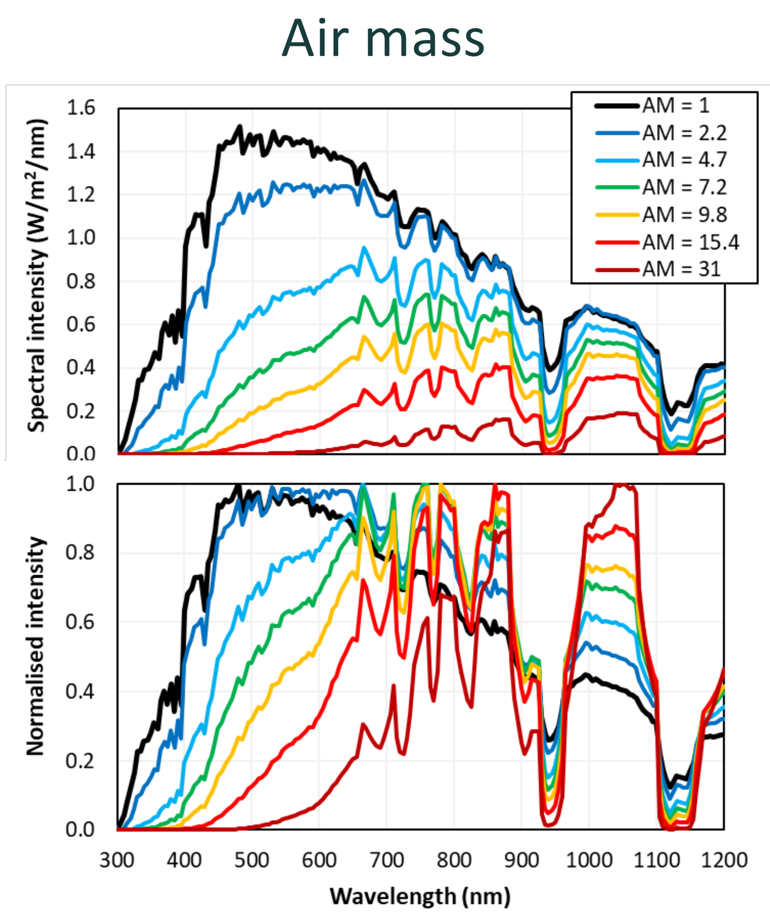
- AM1.5g

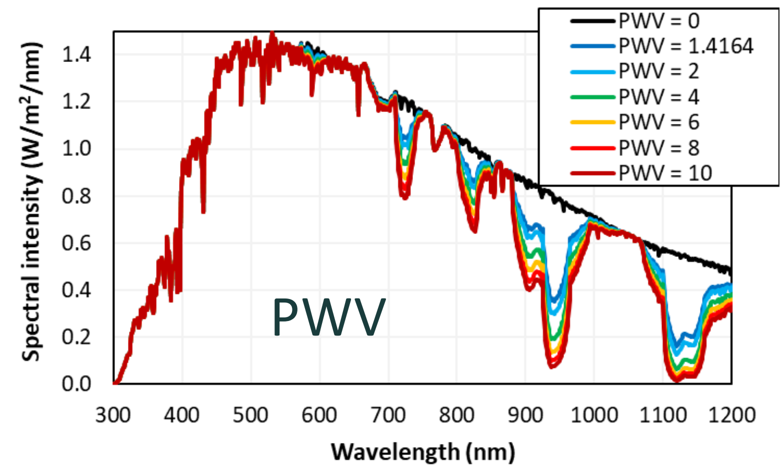
Advanced

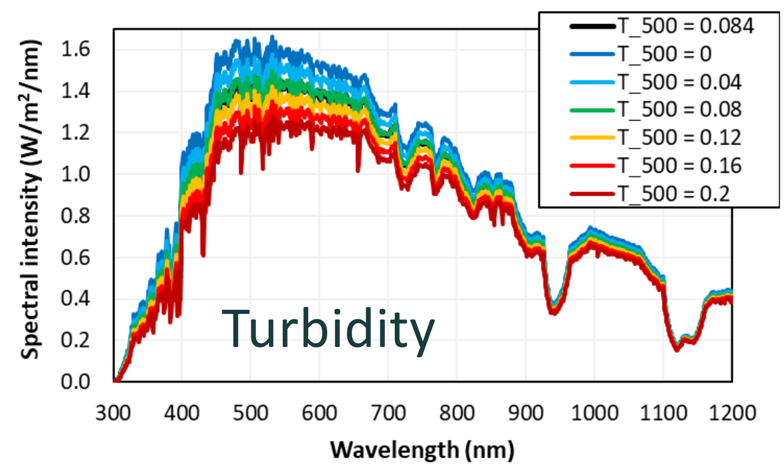
- Calculated at all time steps
  - SPECTRL2 for clear skies [5]
  - Ernst modification for cloudy skies [6]
- Affected by
  - Air mass (i.e., solar location)
  - Precipitable water vapour
  - Turbidity
  - Ozone
  - Air pressure
  - Far-field albedo

[5] Bird and Riordon, "Simple solar spectral model for direct and diffuse irradiance…," *Journal of Climate and Applied Metrology*, **25**, 87–97, 1986.
[6] M. Ernst, et al. "SUNCALCULATOR: A program to calculate the angular and spectral…" *Solar Energy Materials and Solar Cells*, **157** 913–922, 2016.

7. Solar spectra



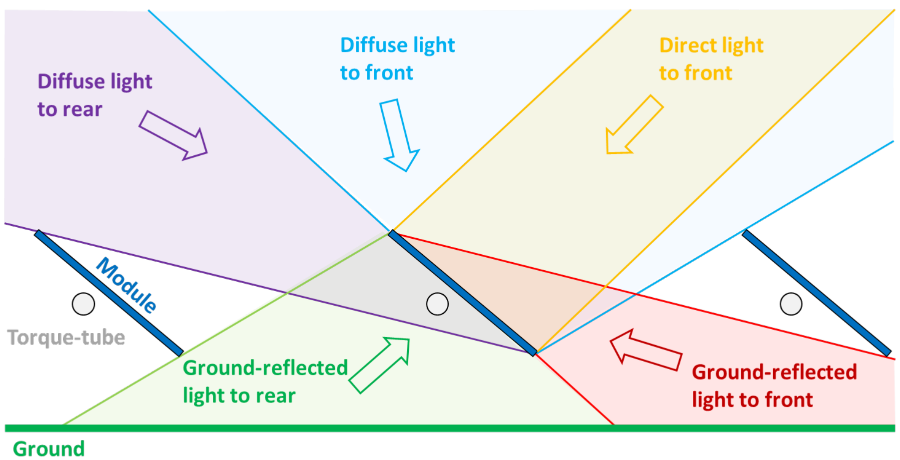




8. System optics

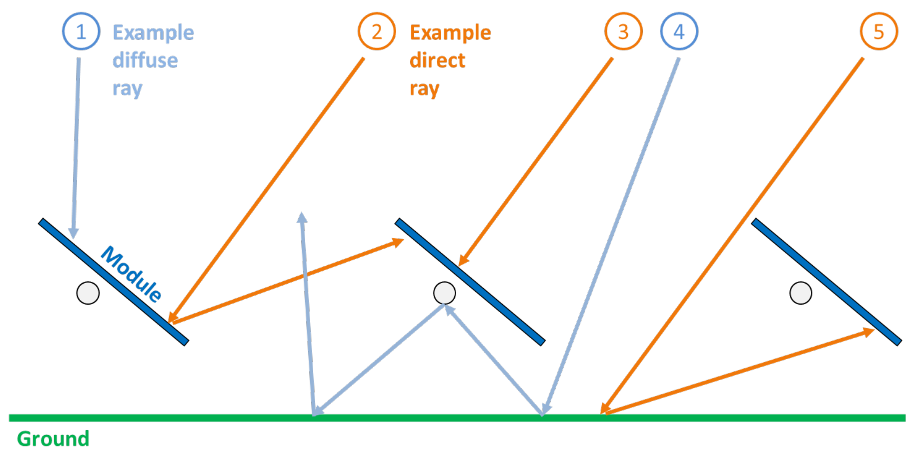
Conventional

- View-factors & bifacial loss factors
  - Structural shading, f_S
  - Transmission, f_T



Advanced

- Ray tracing



8. System optics

PV LIGHTHOUSE

Conventional

- View-factors & bifacial loss factors
  - Structural shading, f_S
  - Transmission, f_T

	f_S	f_T
SAT	9.7%	6.7%
Fixed	19.3%	0.0%
Waves	--	--

Advanced

- Ray tracing

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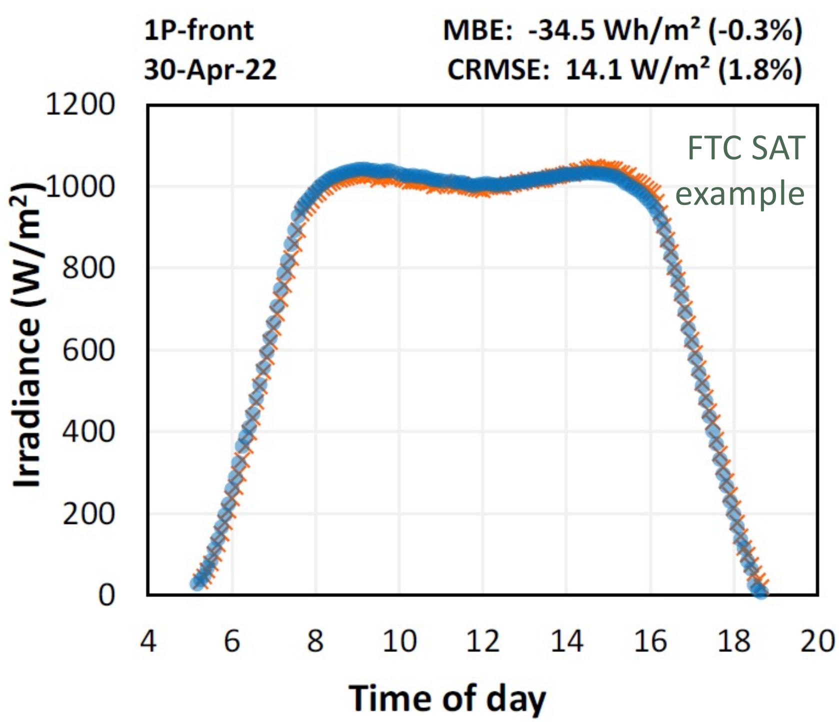

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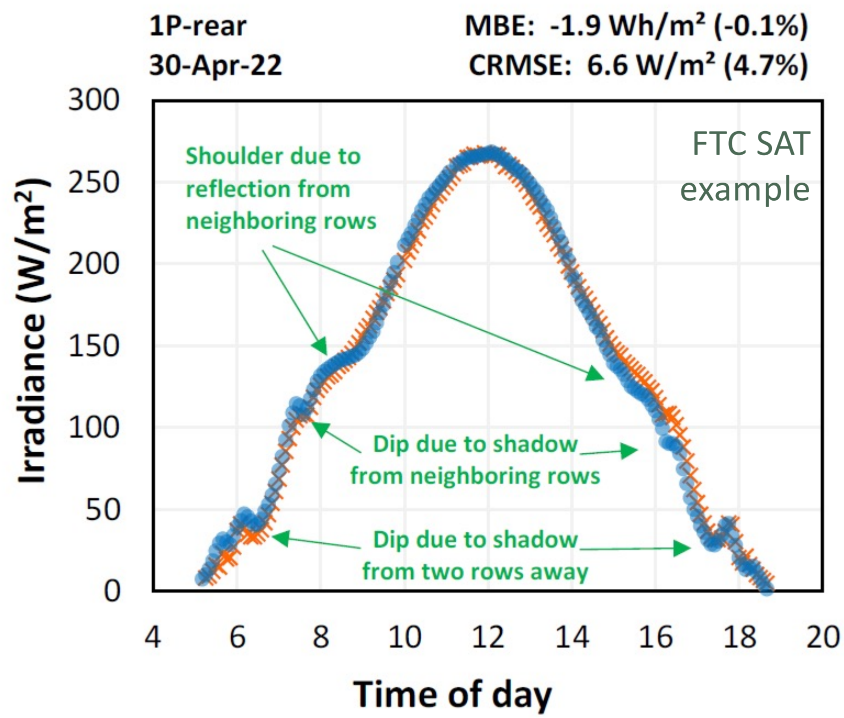
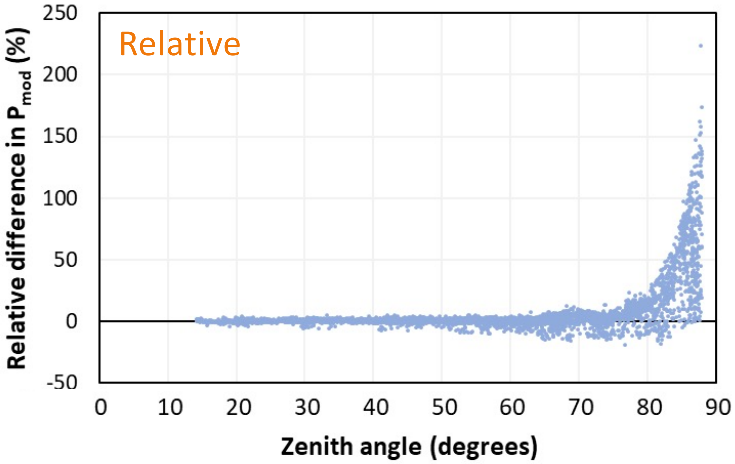


Detailed results for SATs

All mechanisms combined: conventional vs advanced

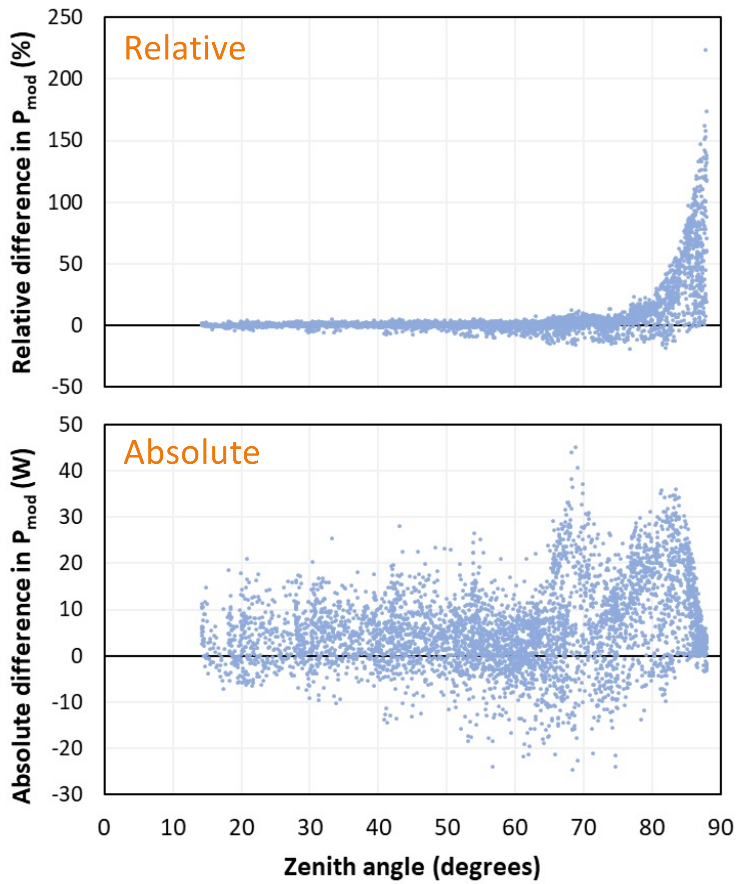


For 1P SAT at Cove Mt, Utah

MBE: +1.90%

CRMSE: 8.9 W

All mechanisms combined: conventional vs advanced



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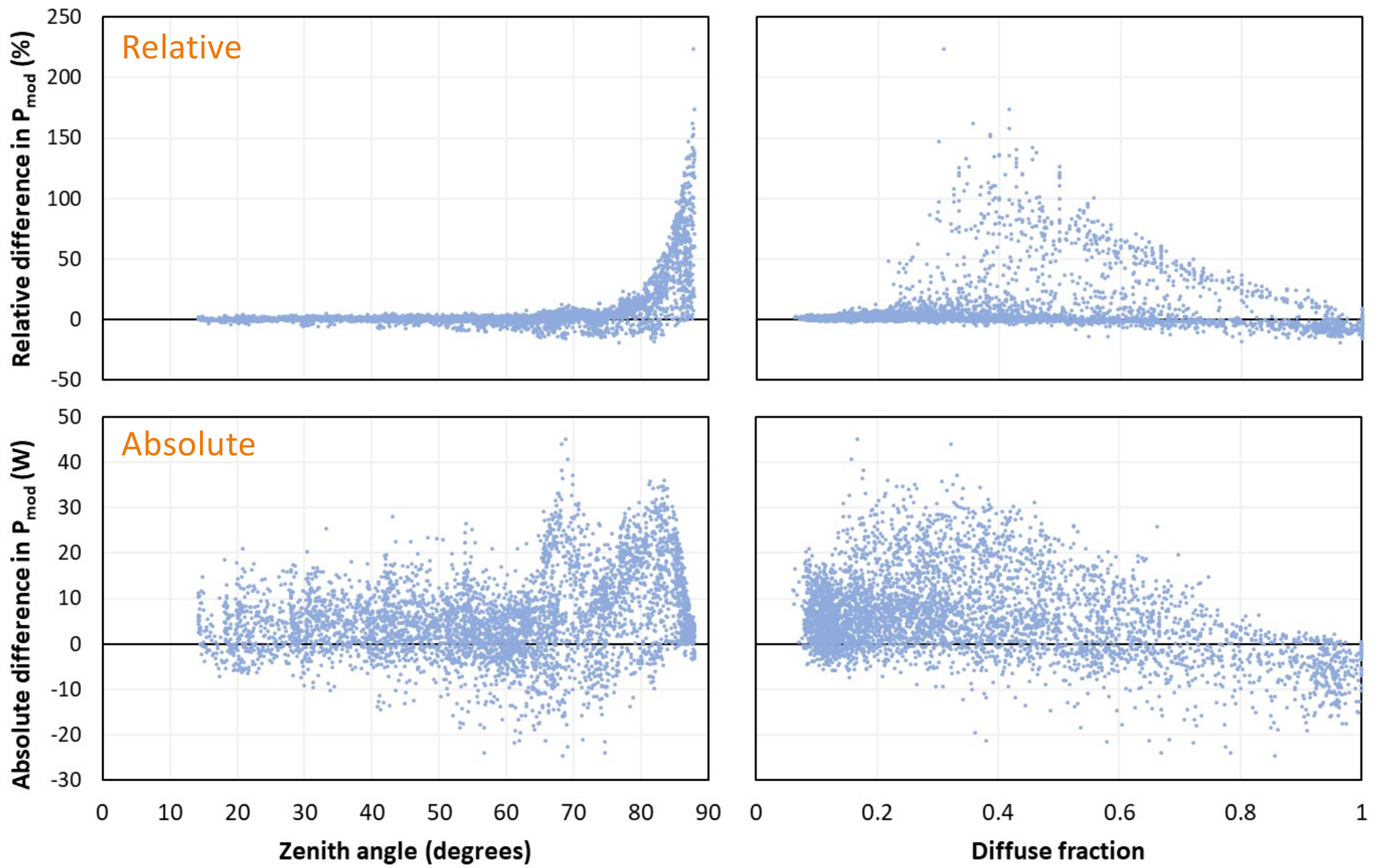

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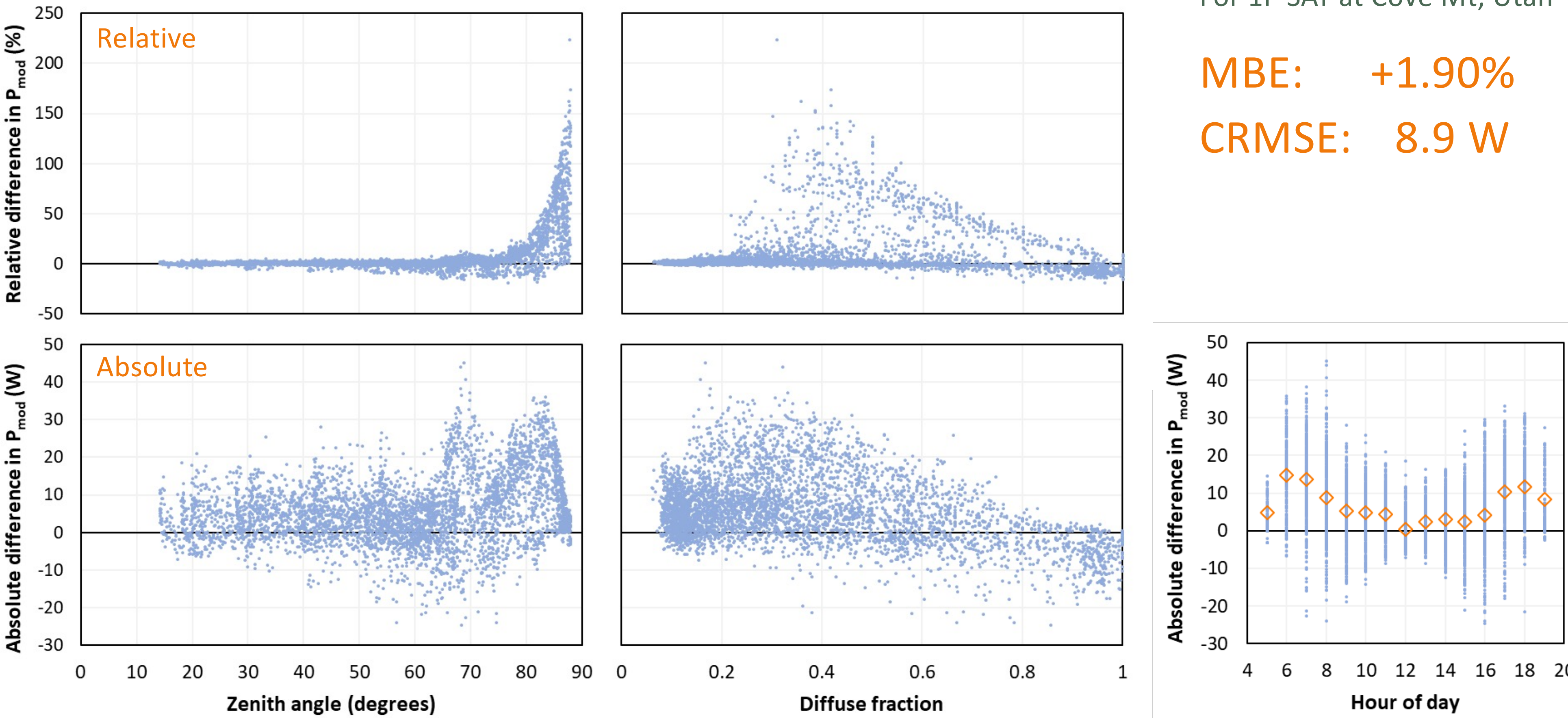
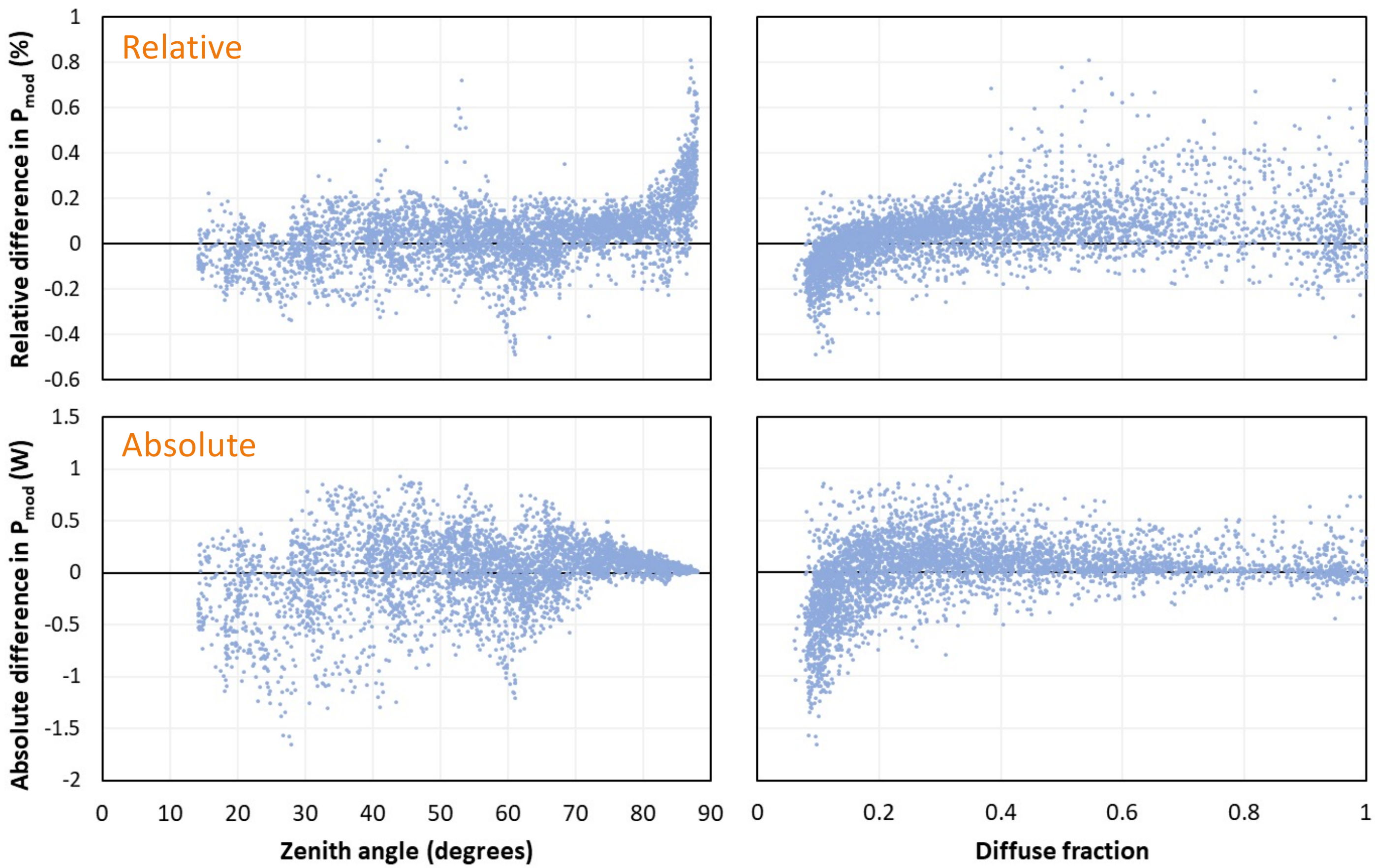


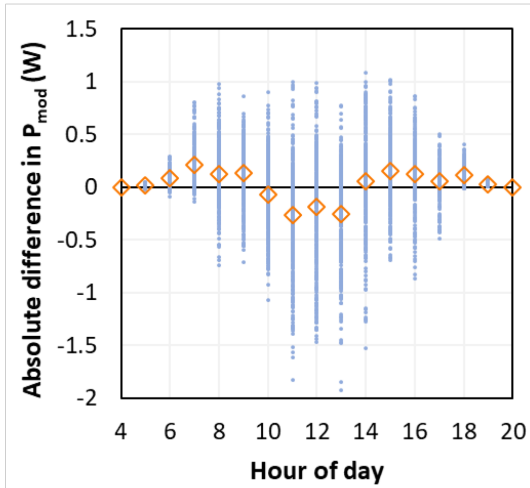
1. Albedo: 33.7% vs yellow-brown soil

For 1P SAT at Cove Mt, Utah

MBE: +0.00%

CRMSE: 0.4 W



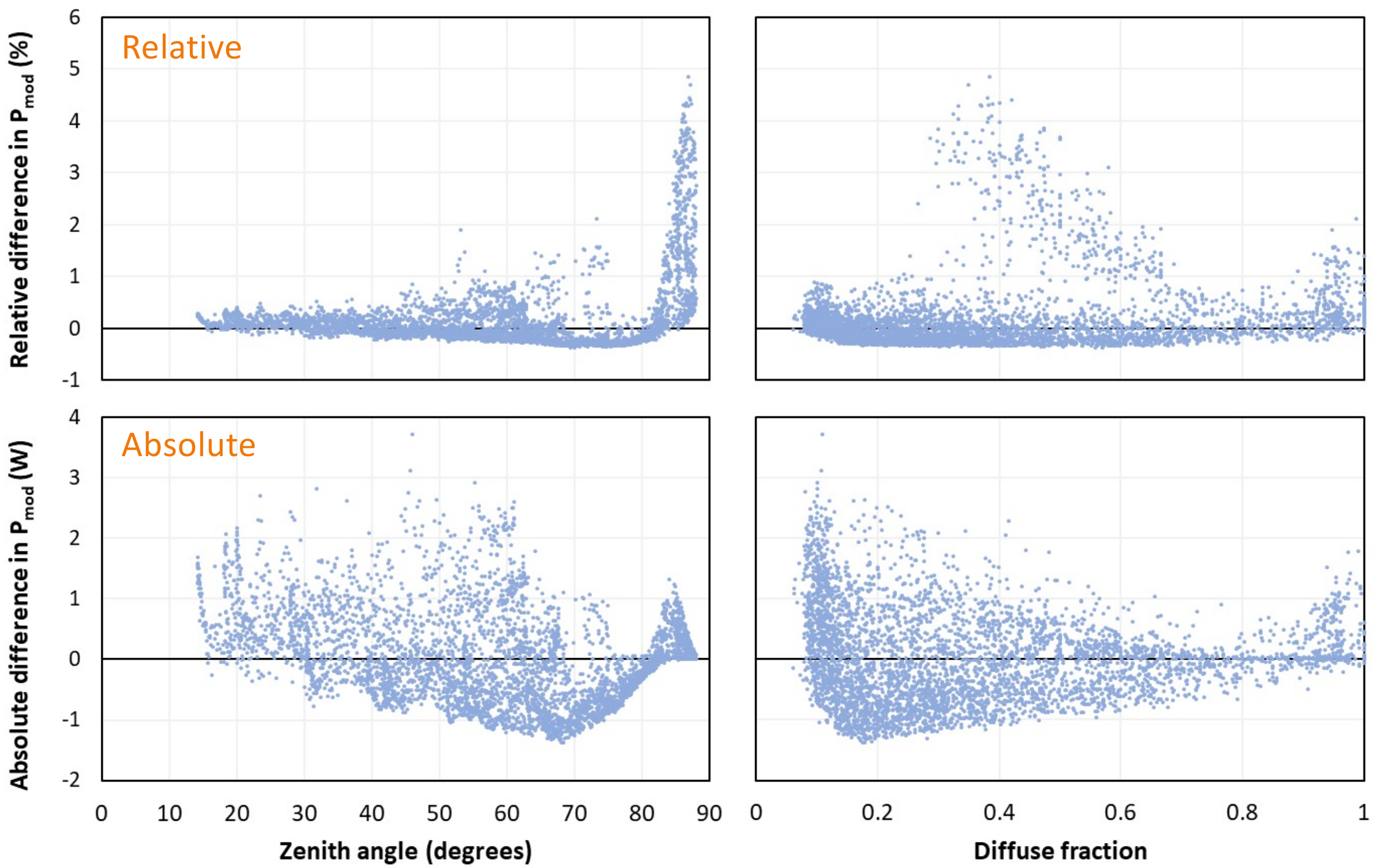


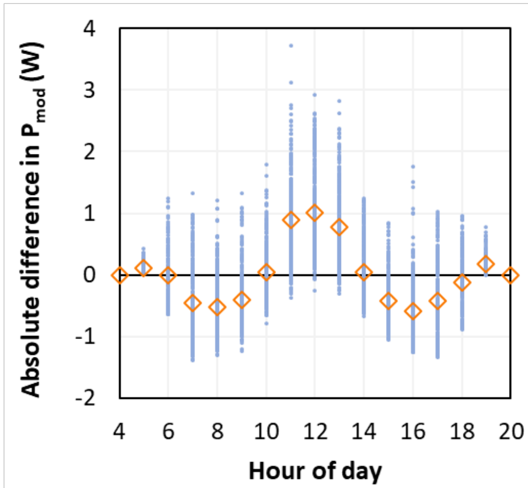
2. Cell-to-cell mismatch: constant vs hour-by-hour

For 1P SAT at Cove Mt, Utah

MBE: +0.00%

CRMSE: 0.8 W



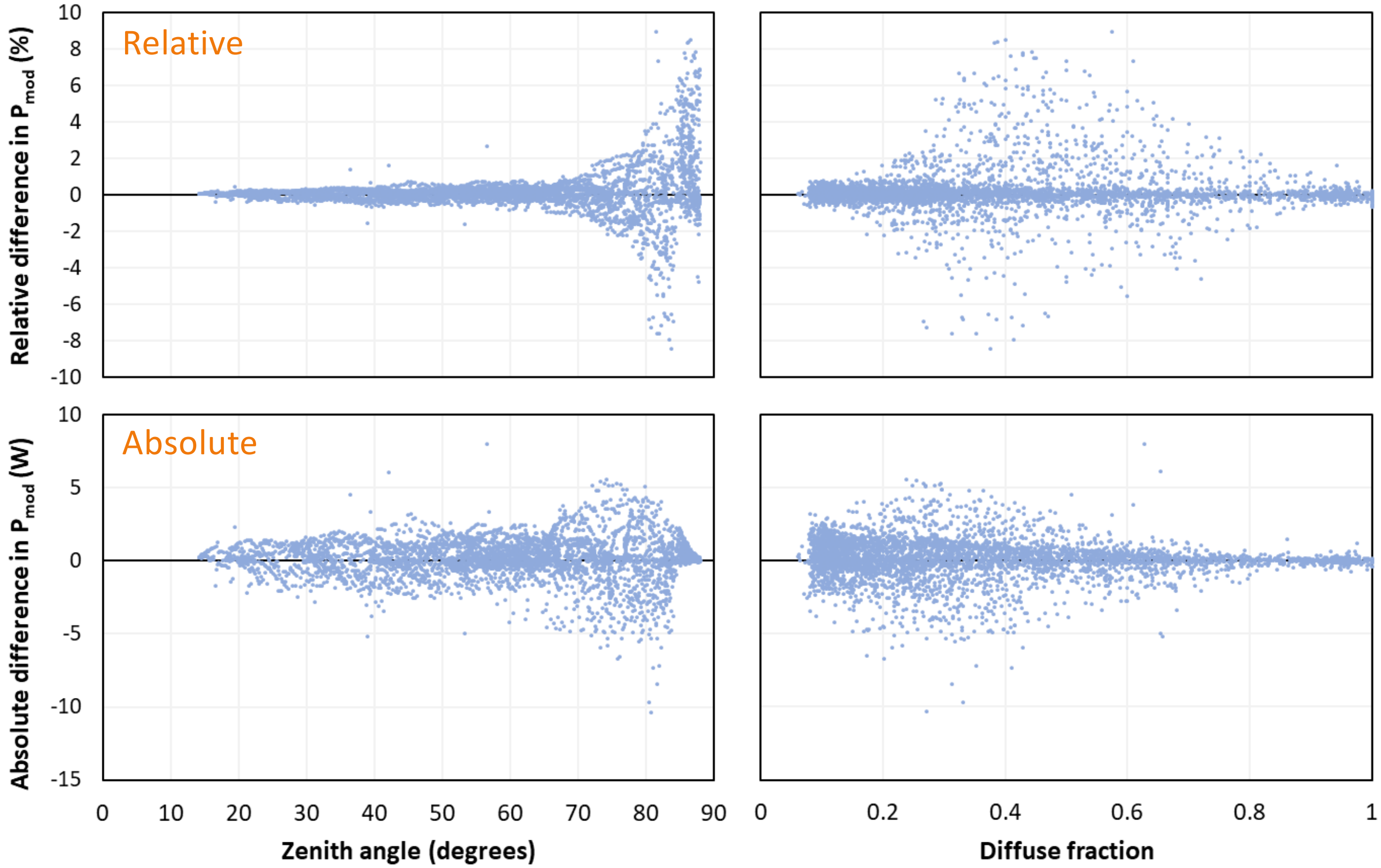


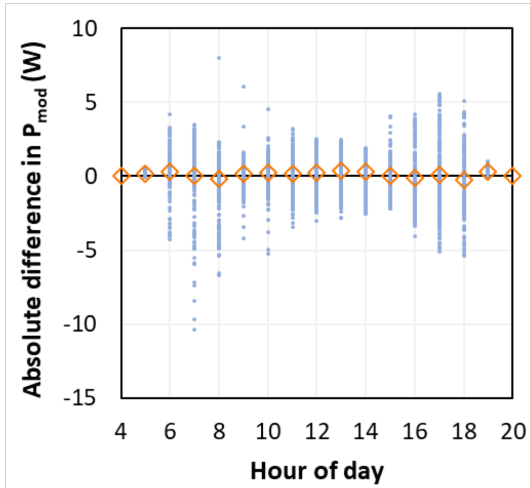
3. Solar position: PVSyst algo vs Reda2004

For 1P SAT at Cove Mt, Utah

MBE: +0.04%

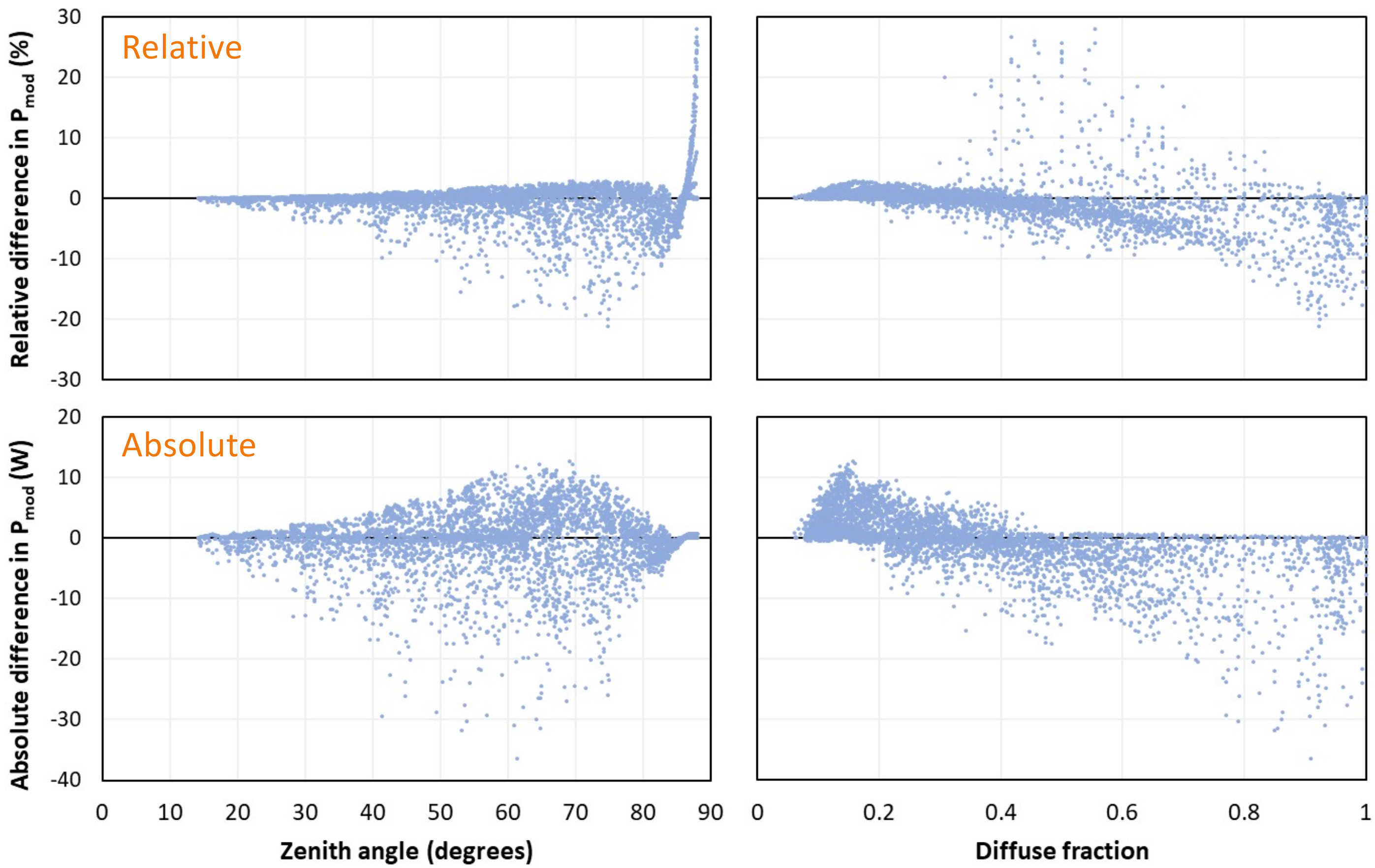
CRMSE: 1.4 W





4. Sky distribution model: Hay–Davies vs Perez 1990

For 1P SAT at Cove Mt, Utah



SunSolve

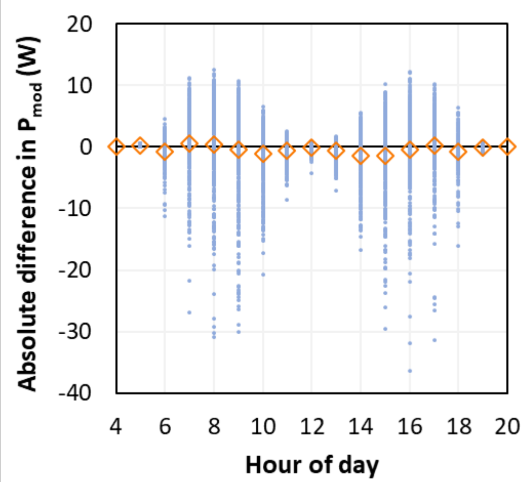
MBE: –0.15%

CRMSE: 5.2 W

PVSyst

MBE: +1.35%

CRMSE: 4.9 W

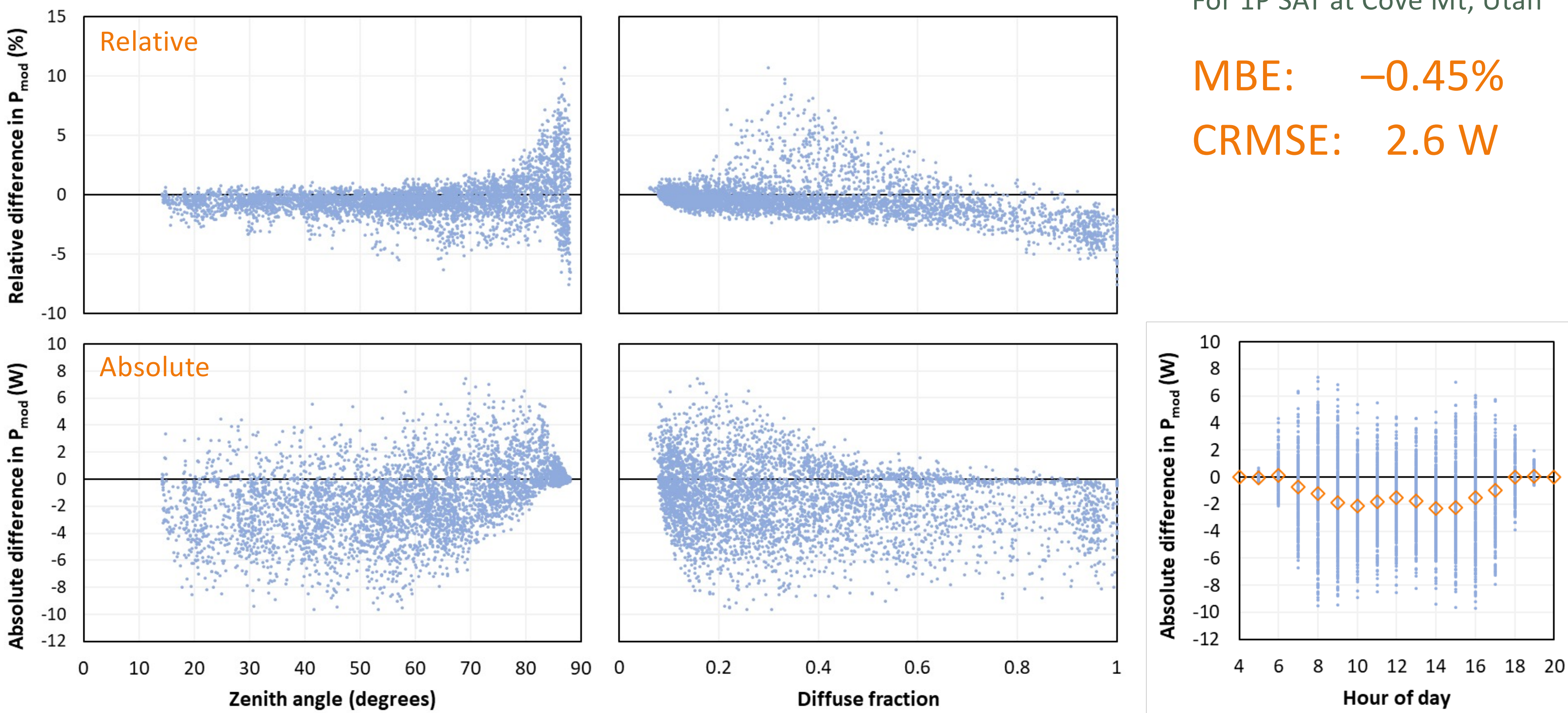


5. Module optics: ‘simple’ vs ray tracing

For 1P SAT at Cove Mt, Utah

MBE: –0.45%

CRMSE: 2.6 W



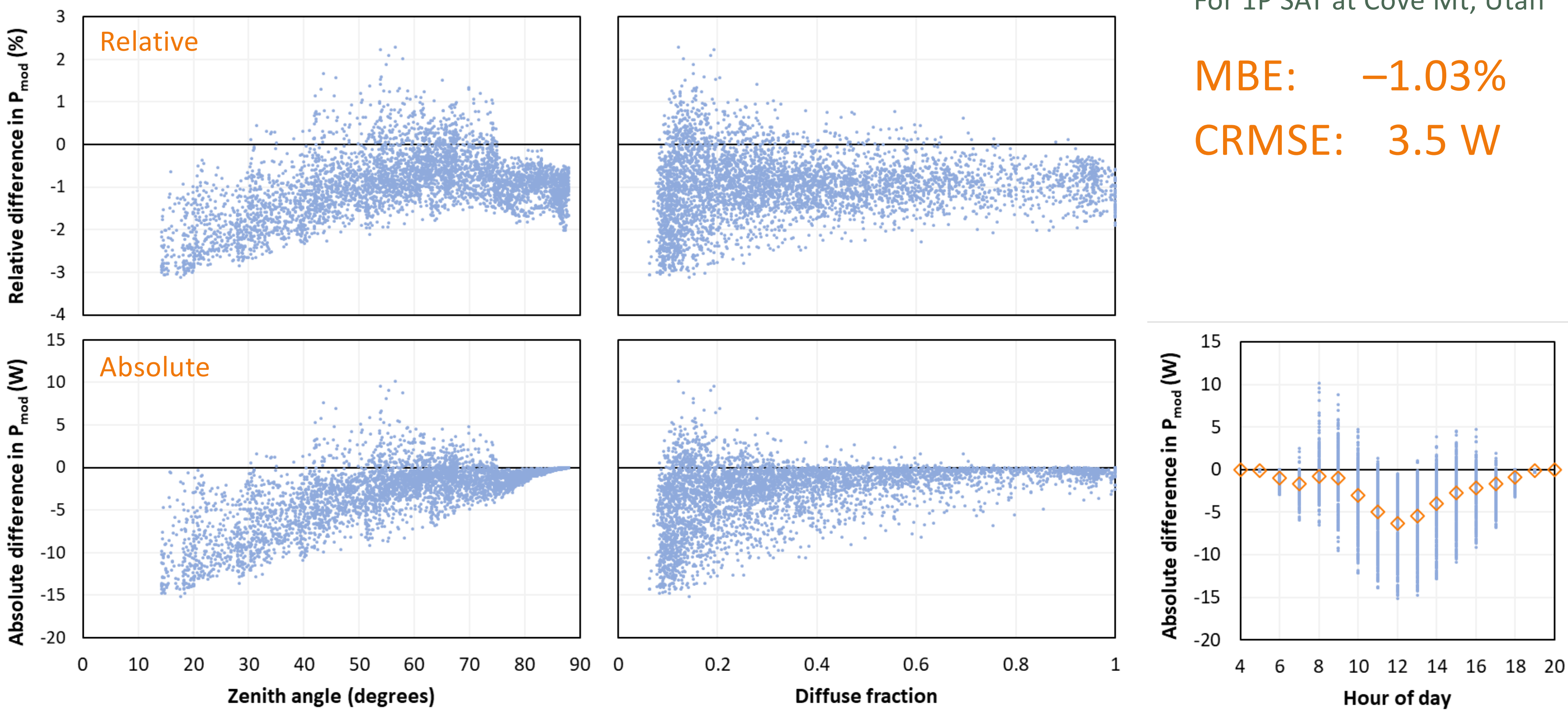
6. Thermal: PVL (tuned) vs Faiman (standard inputs)

PV LIGHTHOUSE

For 1P SAT at Cove Mt, Utah

MBE: –1.03%

CRMSE: 3.5 W

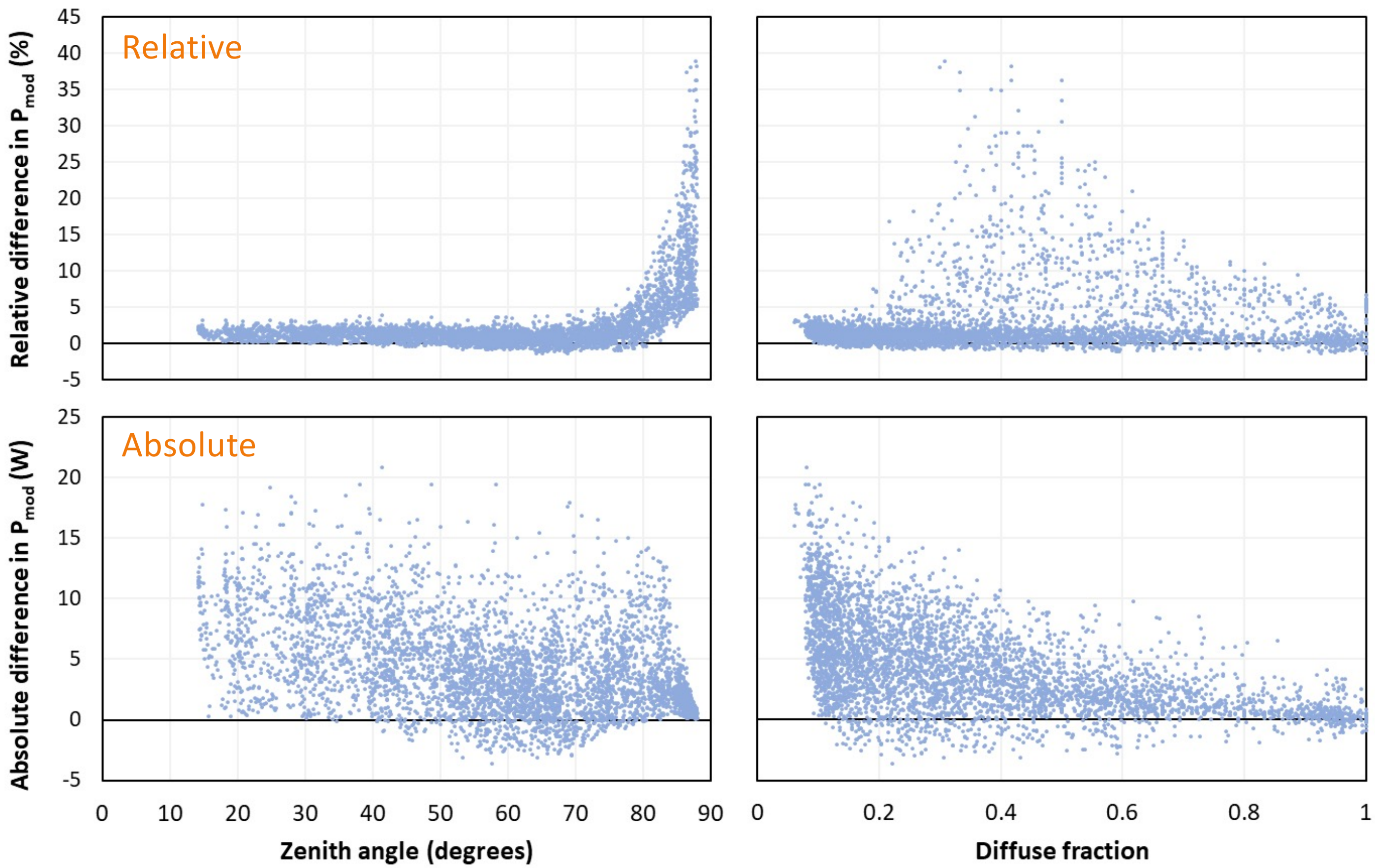


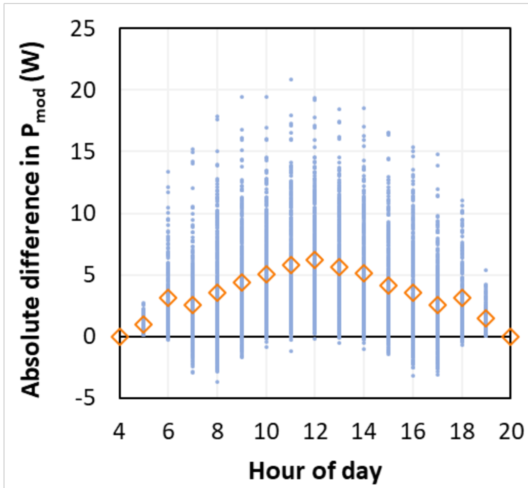
7. Solar spectra: AM1.5g vs SPECTRL2

For 1P SAT at Cove Mt, Utah

MBE: +1.34%

CRMSE: 3.8 W



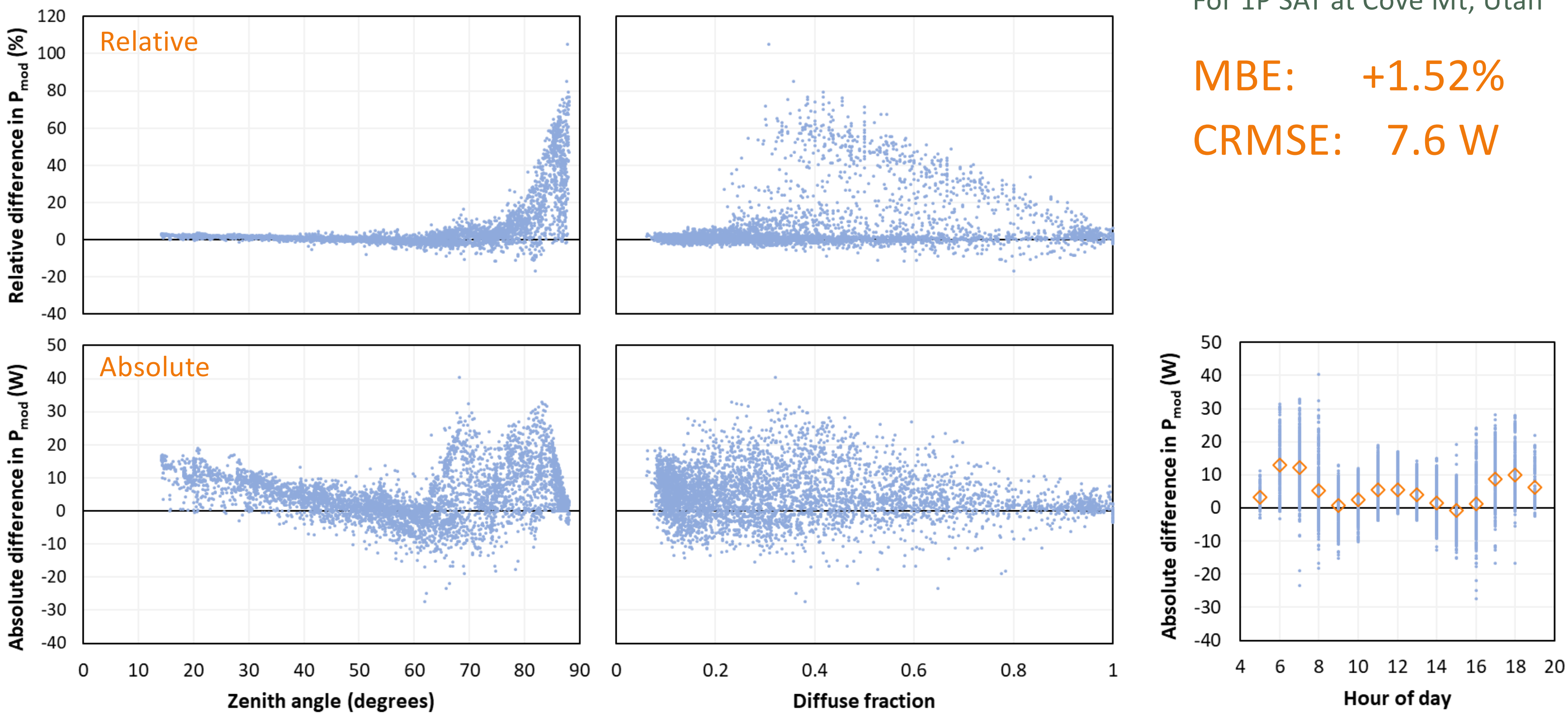


8. System optics: view factor vs ray tracing

For 1P SAT at Cove Mt, Utah

MBE: +1.52%

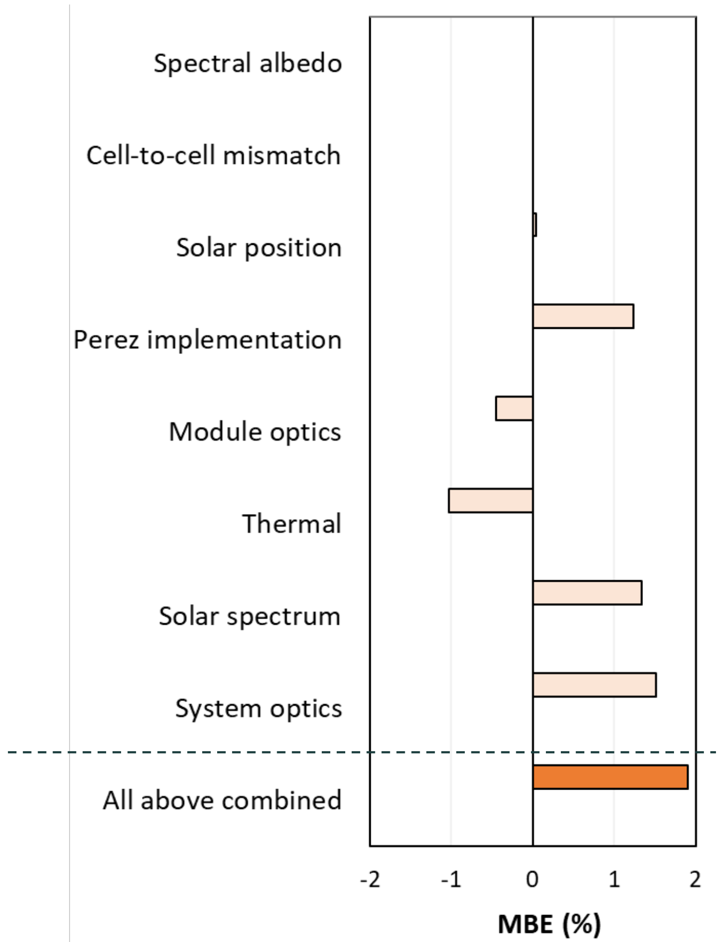
CRMSE: 7.6 W



Results summary
& conclusions

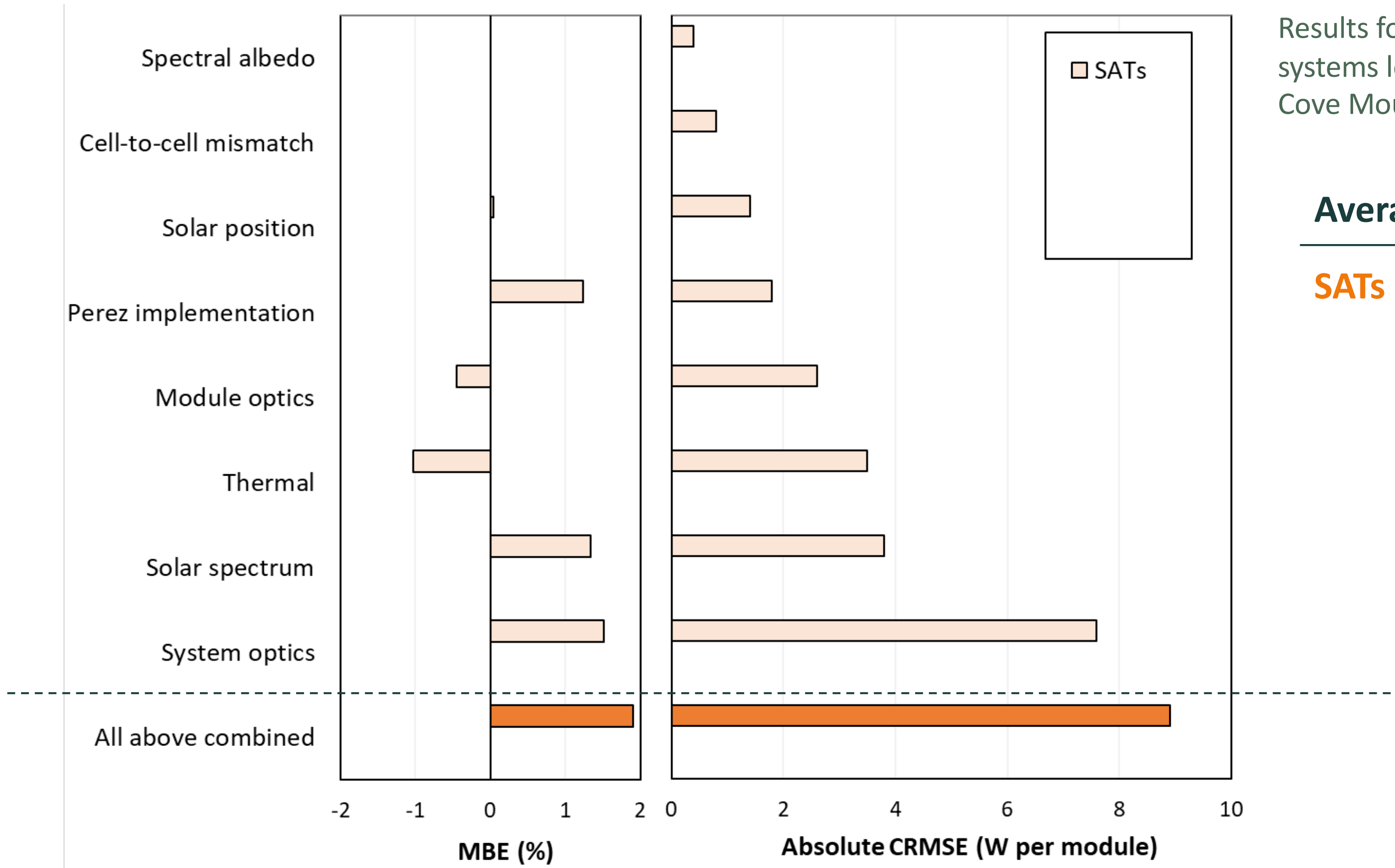
Results summary

PV LIGHTHOUSE



Results for typical systems located at Cove Mountain, UT.

Results summary

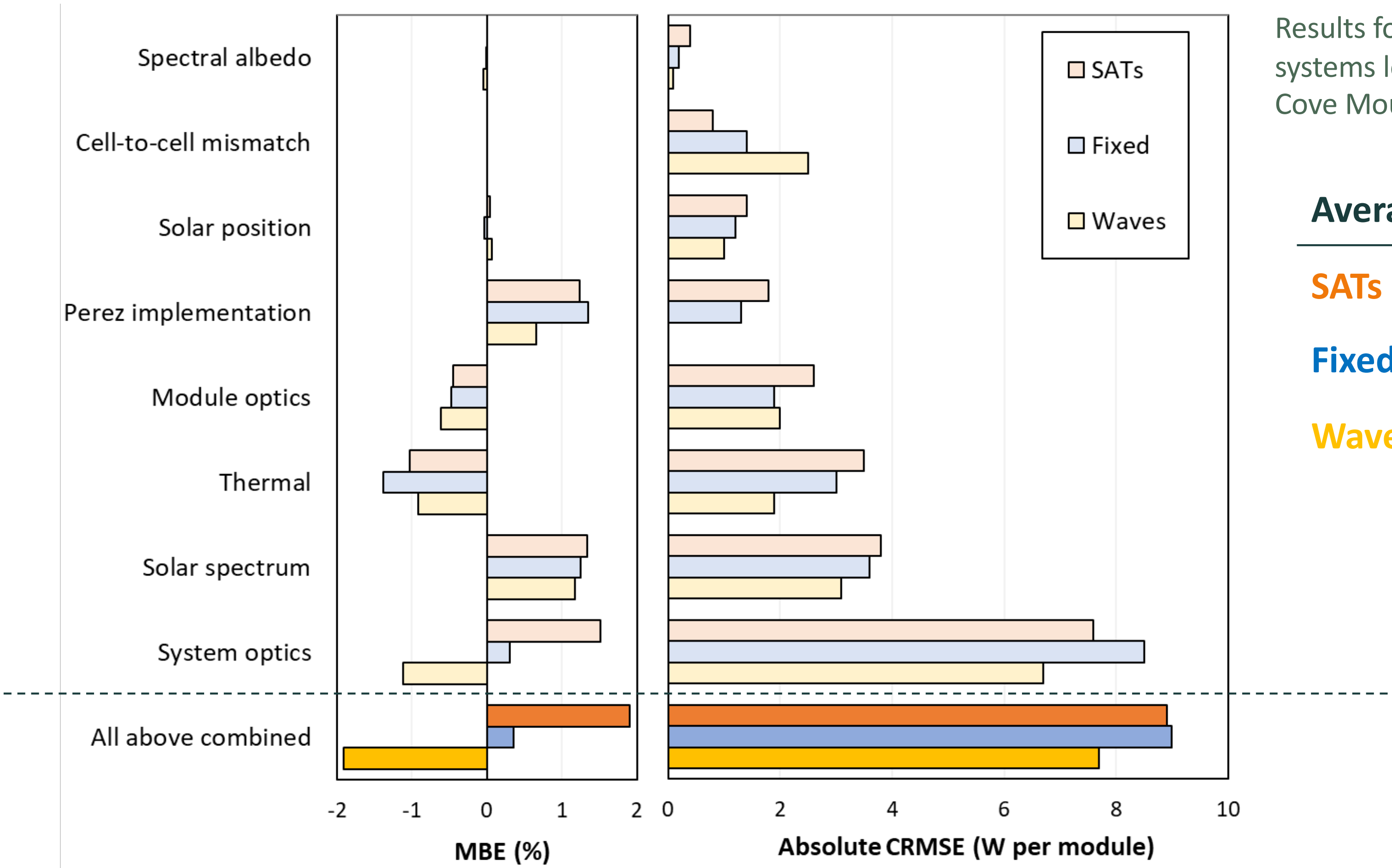


Results for typical systems located at Cove Mountain, UT.

Average P_{mod}	
SATs	315 W

Results summary

PV LIGHTHOUSE



Results for typical systems located at Cove Mountain, UT.

Average P_{mod}	
SATs	315 W
Fixed	254 W
Waves	224 W

Conclusions

PV LIGHTHOUSE

- Simulated examples for the site of Cove Mountain plant south-west Utah.
- Largest sources of difference between conventional and advanced models:
  - System optics (VF vs RT)
  - Solar spectrum
  - Thermal
  - Module optics
  - Diffuse sky distribution
- All conventional vs all advanced

	MBE	2 × CRMSE	2 × CRMSE / P_{mod}
SAT	+1.9%	18 W/mod	5.7%
Fixed	+0.4%	18 W/mod	7.1%
Waves	–1.9%	15 W/mod	6.9%

If MBE were zero (e.g., by derating module), then with 95% confidence, at any given time, the models would predict the same P_{mod} to within

- ±15–18 W
- Equivalent to ±6–7% of the average P_{mod}.

Thank you

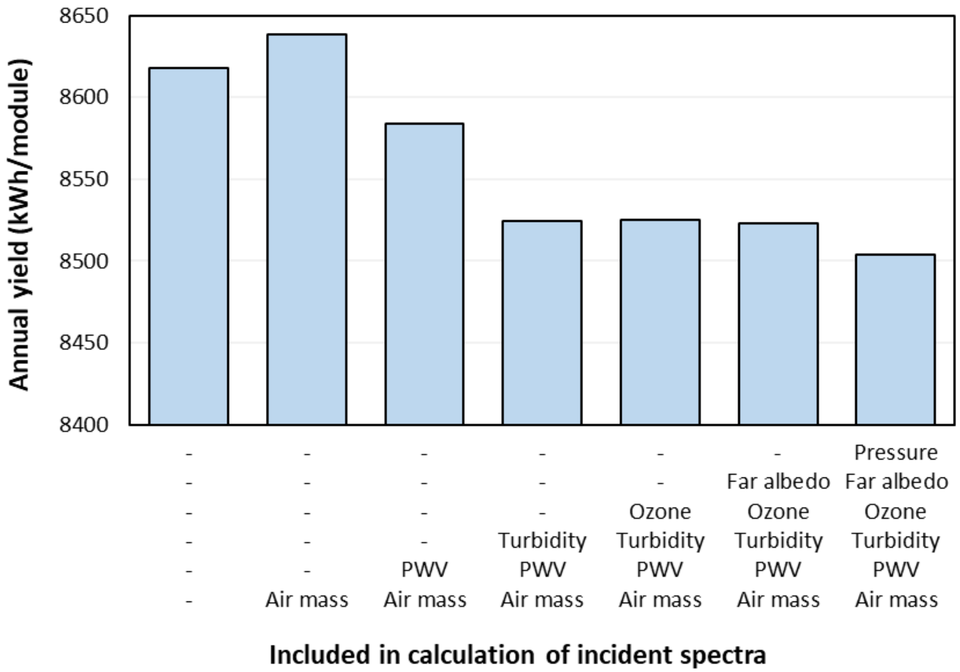
PV LIGHTHOUSE

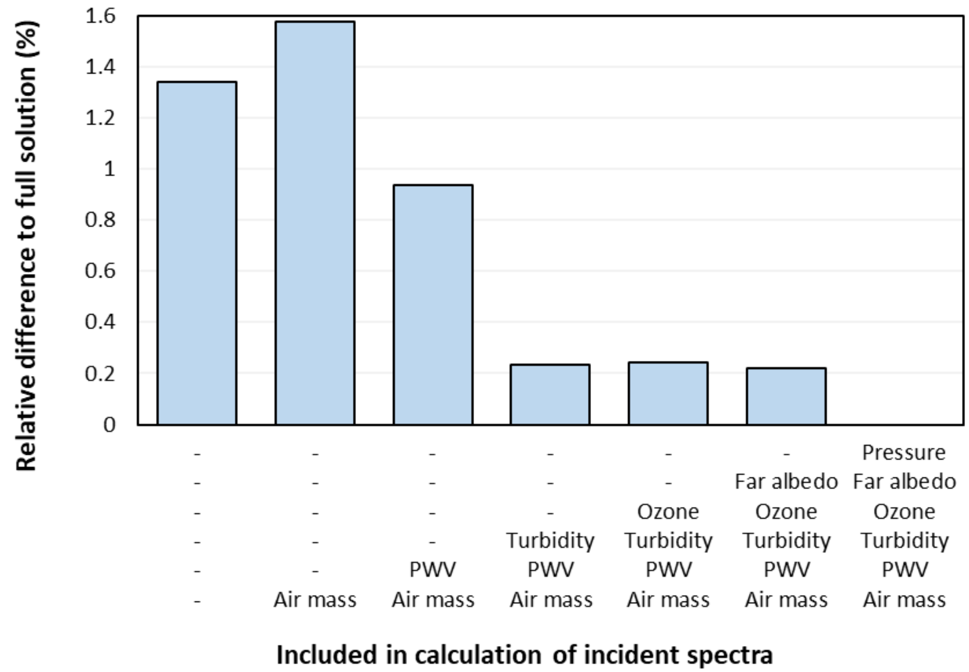
Attendees of the PVPMC workshop 2023 are welcome to an extended free trial of SunSolve-Yield

Register with this QR code during PVPMC 2023 to receive a free trial with twice the normal simulation allowance.

Appendix

Solar spectra: dependence on atmosphere (SATs)

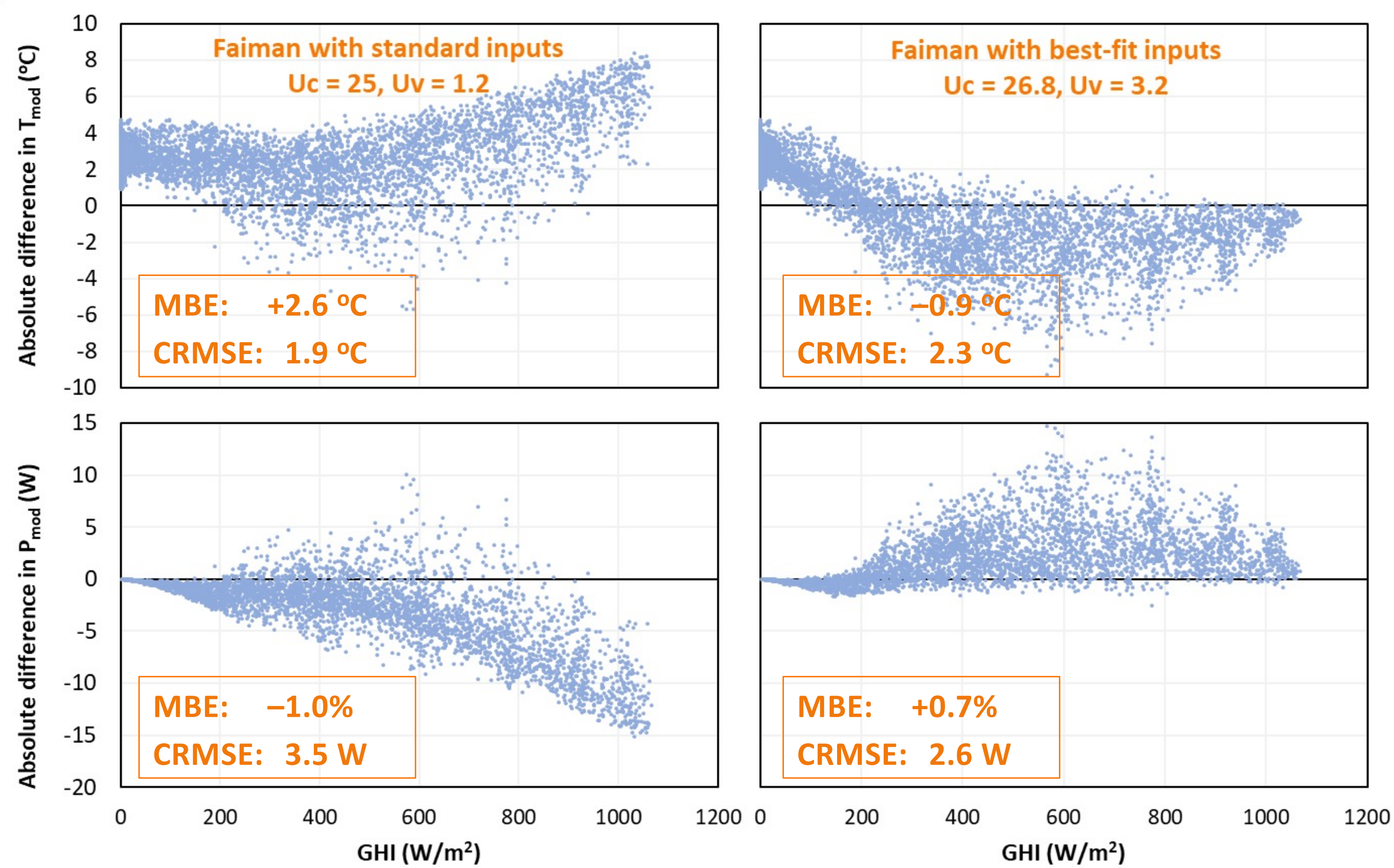




Thermal model: Faiman vs PVL

Absolute difference in temperature

Absolute difference in power



A few more details

PV LIGHTHOUSE

Conventional

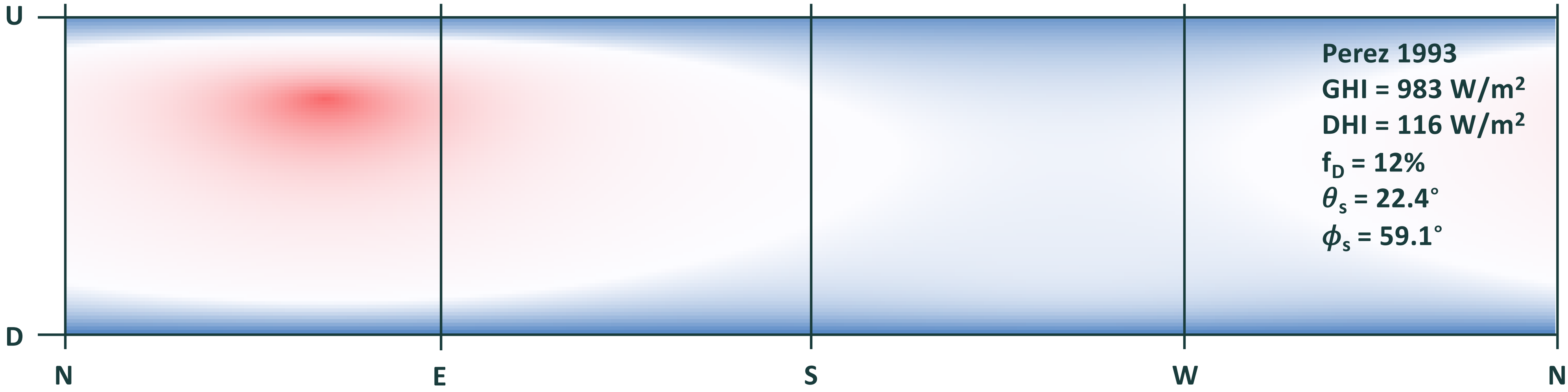
- VF:
  - Unlimited trackers, sheds or domes
  - 999 rows (max)

Advanced

- RT:
  - 1M rays per module per condition
  - 10 min RT for full < 1 min for simple

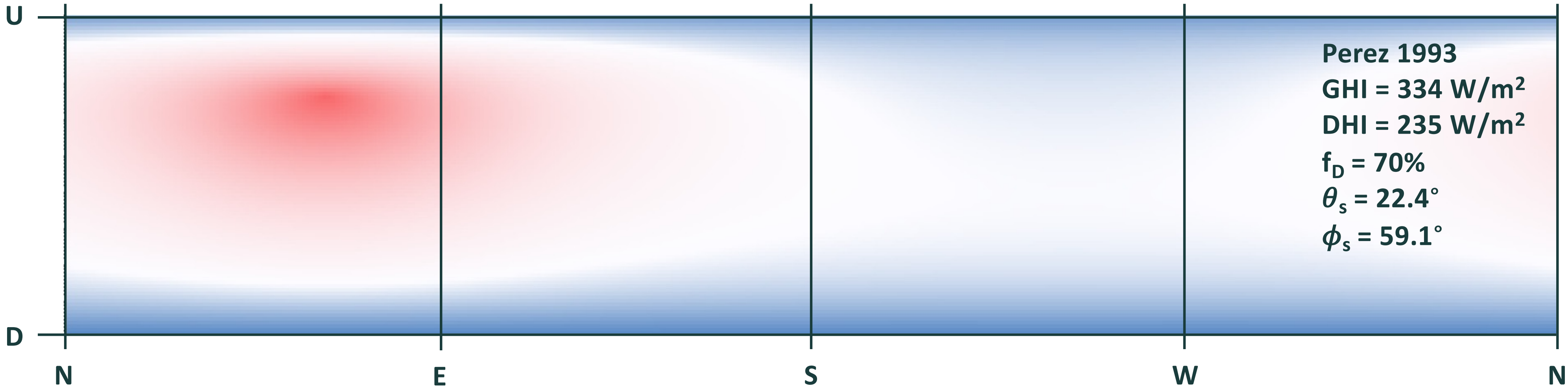
Diffuse sky distribution

- When solved with advanced Perez model (1993).
- 12% diffuse.



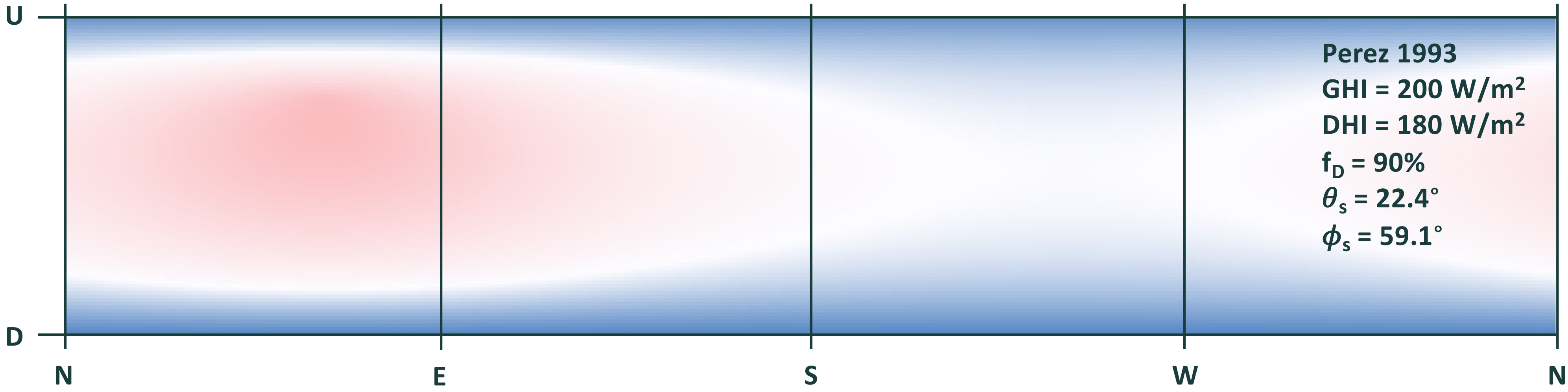
Diffuse sky distribution

- When solved with advanced Perez model (1993).
- 70% diffuse.



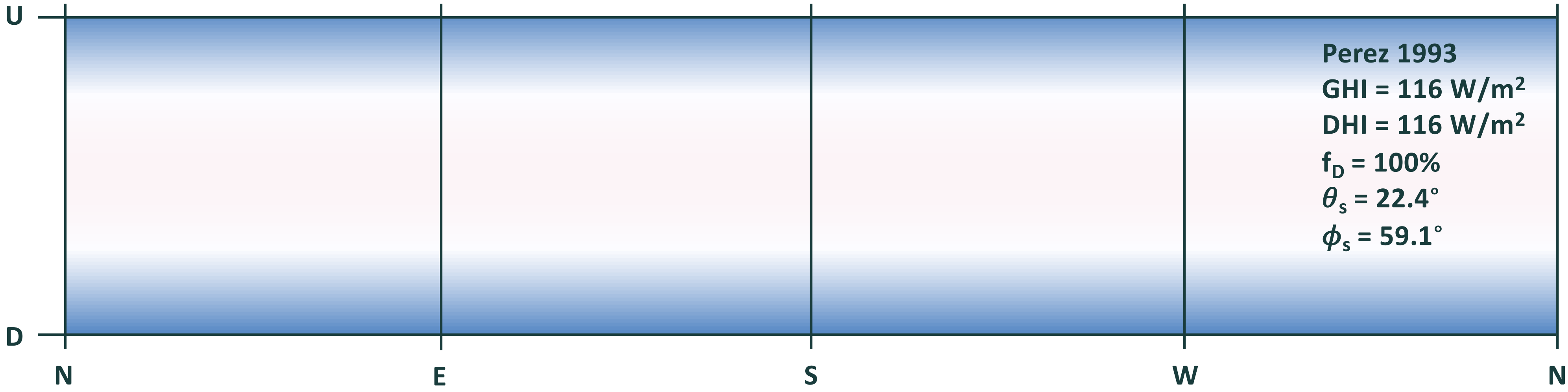
Diffuse sky distribution

- When solved with advanced Perez model (1993).
- 90% diffuse.



Diffuse sky distribution

- When solved with advanced Perez model (1993).
- 100% diffuse.

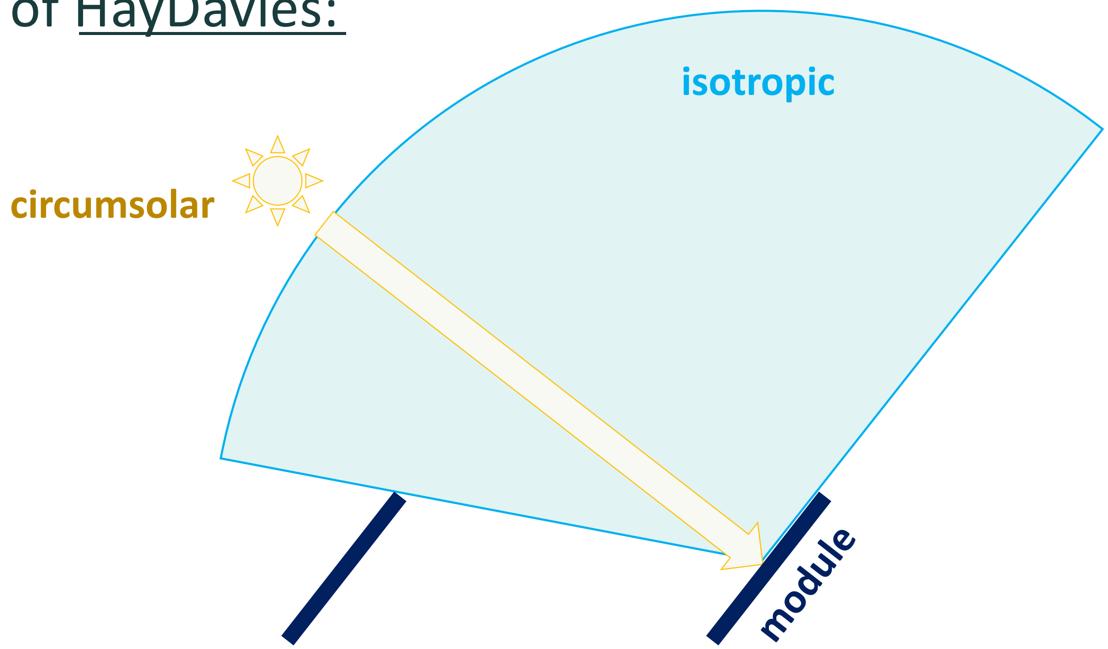


Diffuse sky distribution

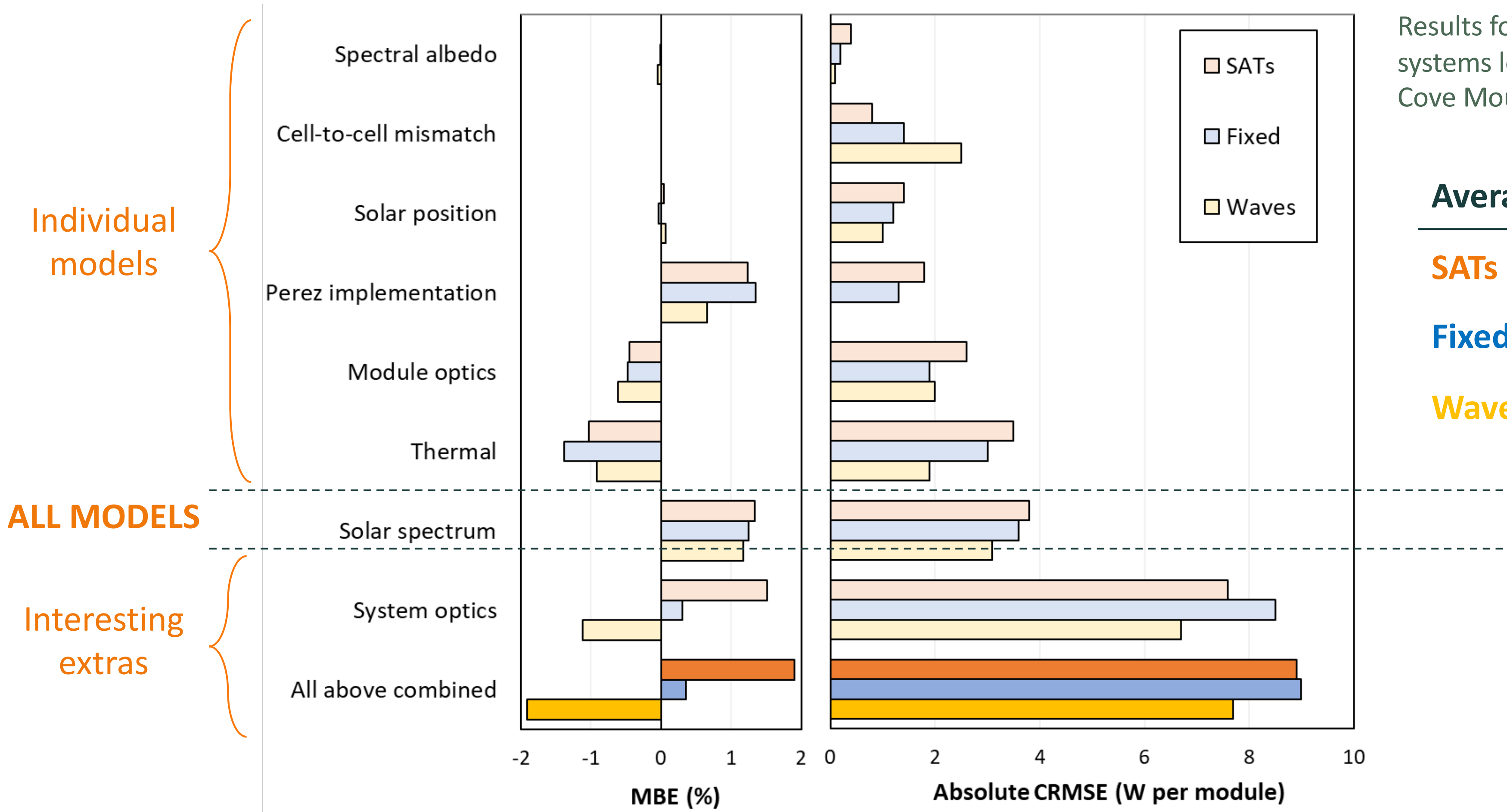
- Adaption for infinite field accounts for shading from modules.

- Both implementations of HayDavies:

- isotropic
  - partial shading
- circumsolar
  - possible shading
- horizon
  - none



Results summary



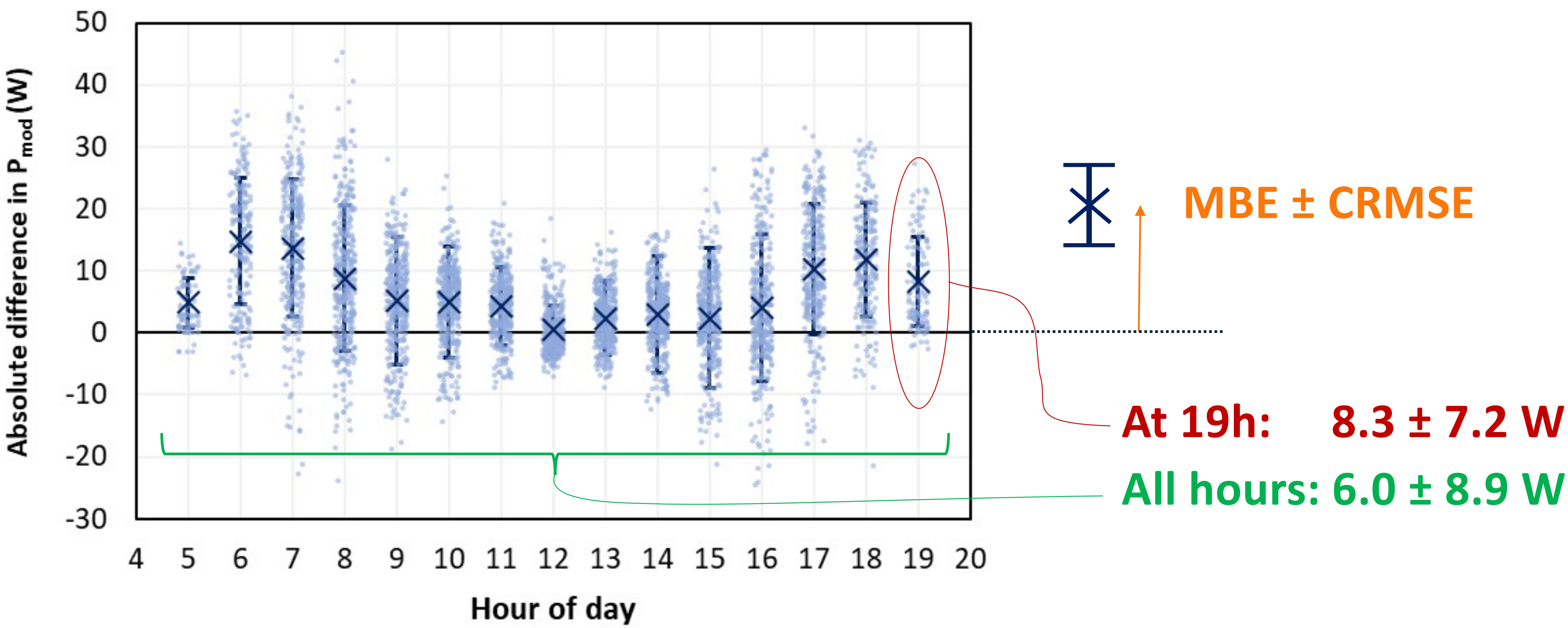
Results for typical systems located at Cove Mountain, UT.

Average P_{mod}	
SATs	315 W
Fixed	254 W
Waves	224 W

Metrics

PV LIGHTHOUSE

Difference between two models quantified with MBE & CRMSE.



5. Module optics: 'simple' vs ray tracing with crazy IAM

For 1P SAT at Cove Mt, Utah

MBE: +0.96%

CRMSE: 4.2 W