SunSolve

UNSW
27 August 2024

PV LIGHTHOUSE

Keith McIntosh

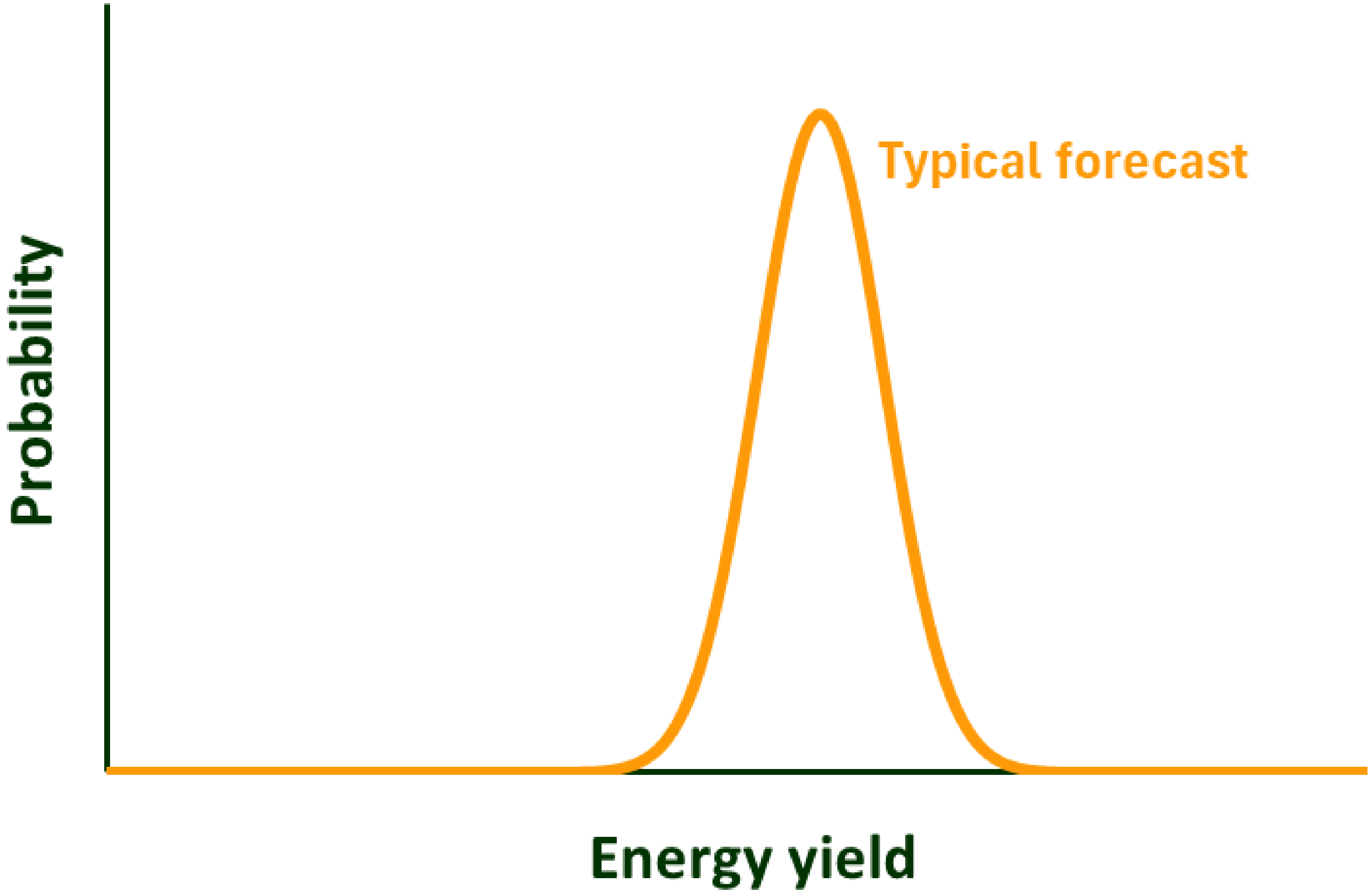
ARENA project

SunSolve

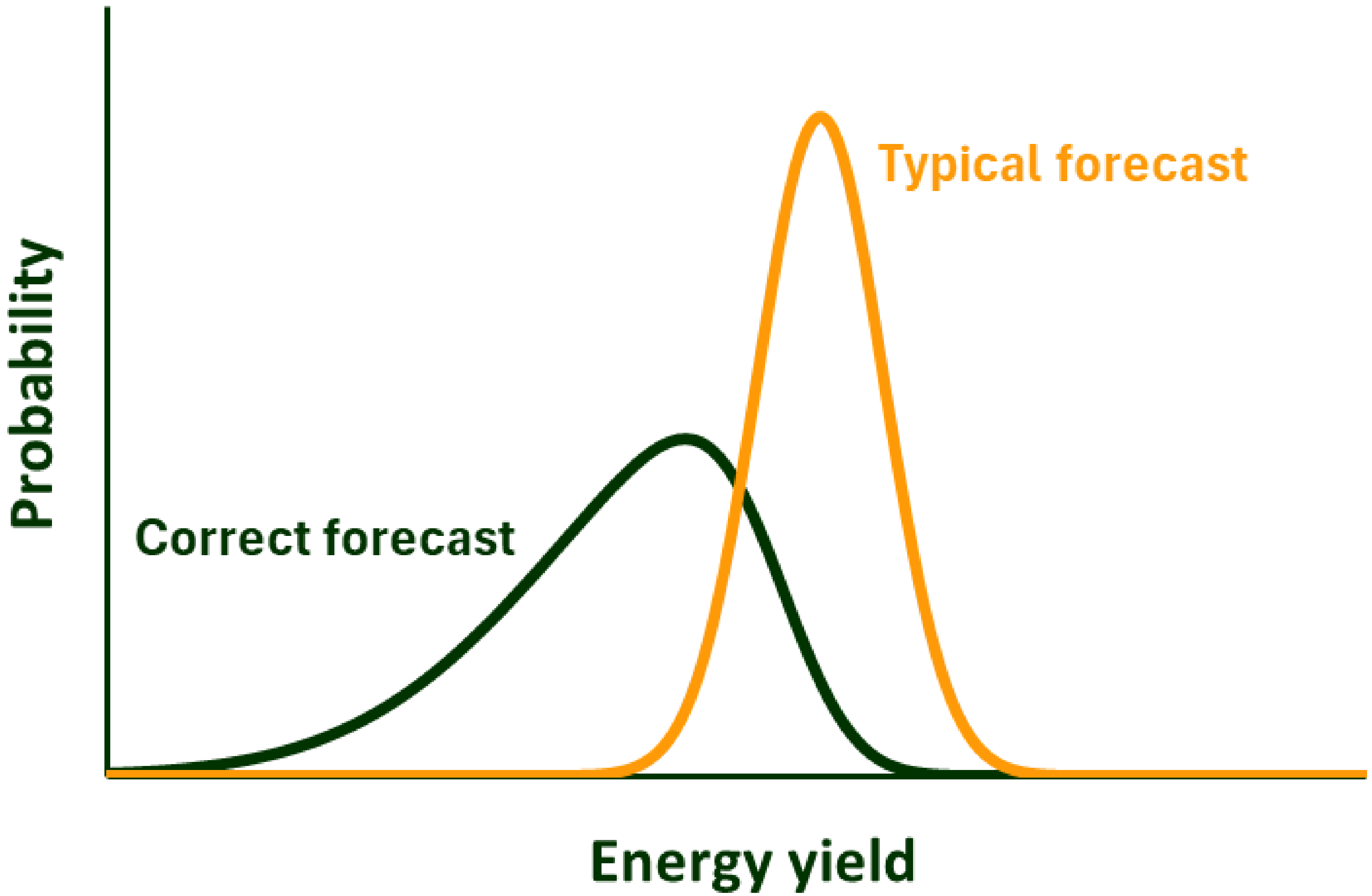
Image from Novergy Solar, https://www.novergysolar.com/solar-string-inverters-better-utility-scale-solar-plants-industrial-solar-projects/

ARENA project

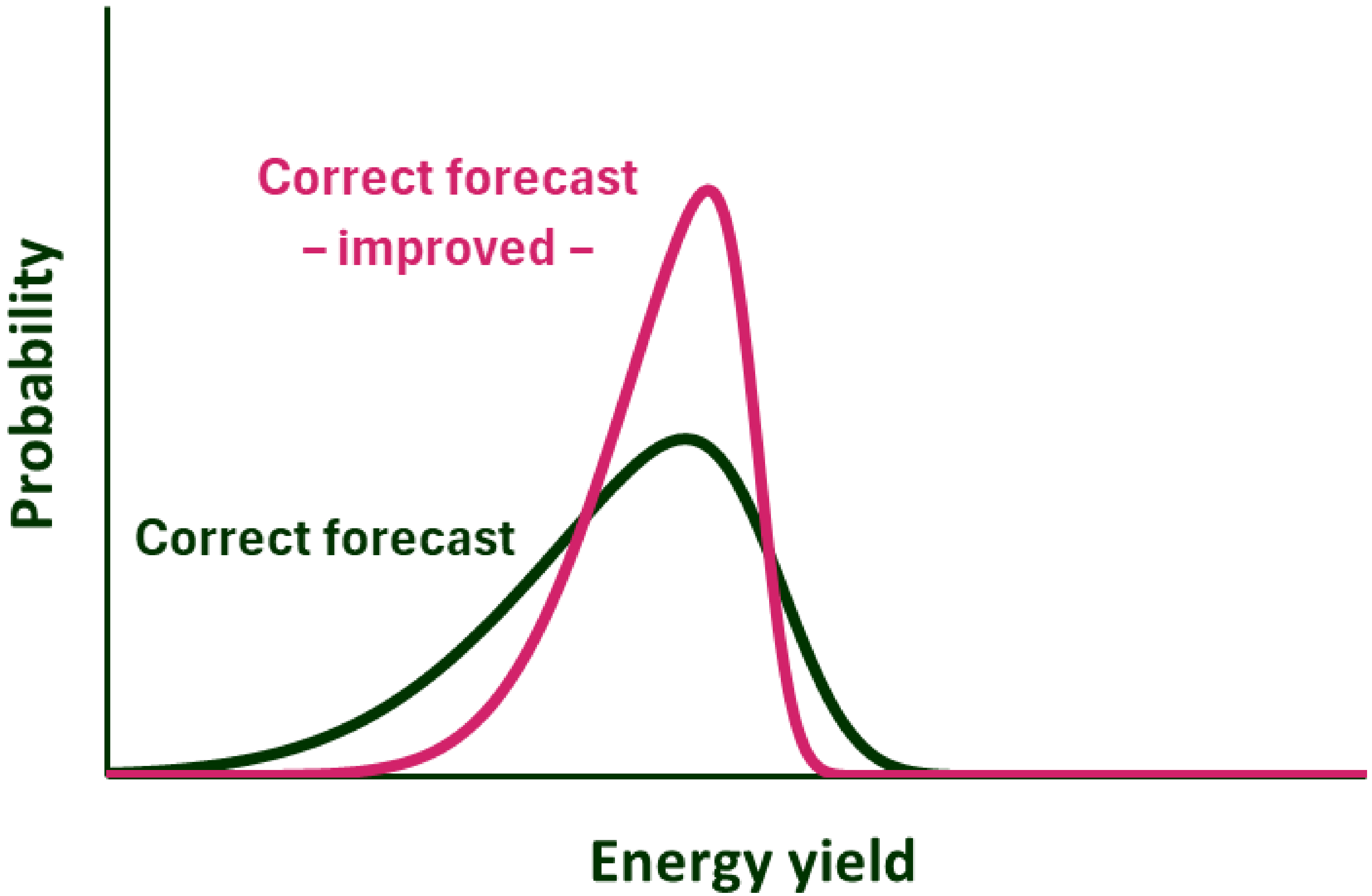
SunSolve



SunSolve


Typical forecast
Probability
Correct forecast
Energy yield

SunSolve


Correct forecast
– improved –
Correct forecast
Probability
Energy yield

ARENA project

SunSolve

- “Accurate and precise solar yield modelling with SunSolve”
  - Develop and validate algorithms, procedures and software
  - Improve forecasts of the energy produced by PV power plants

- 3 years
  - 18-Jun-2024 to 18-Jun-2027

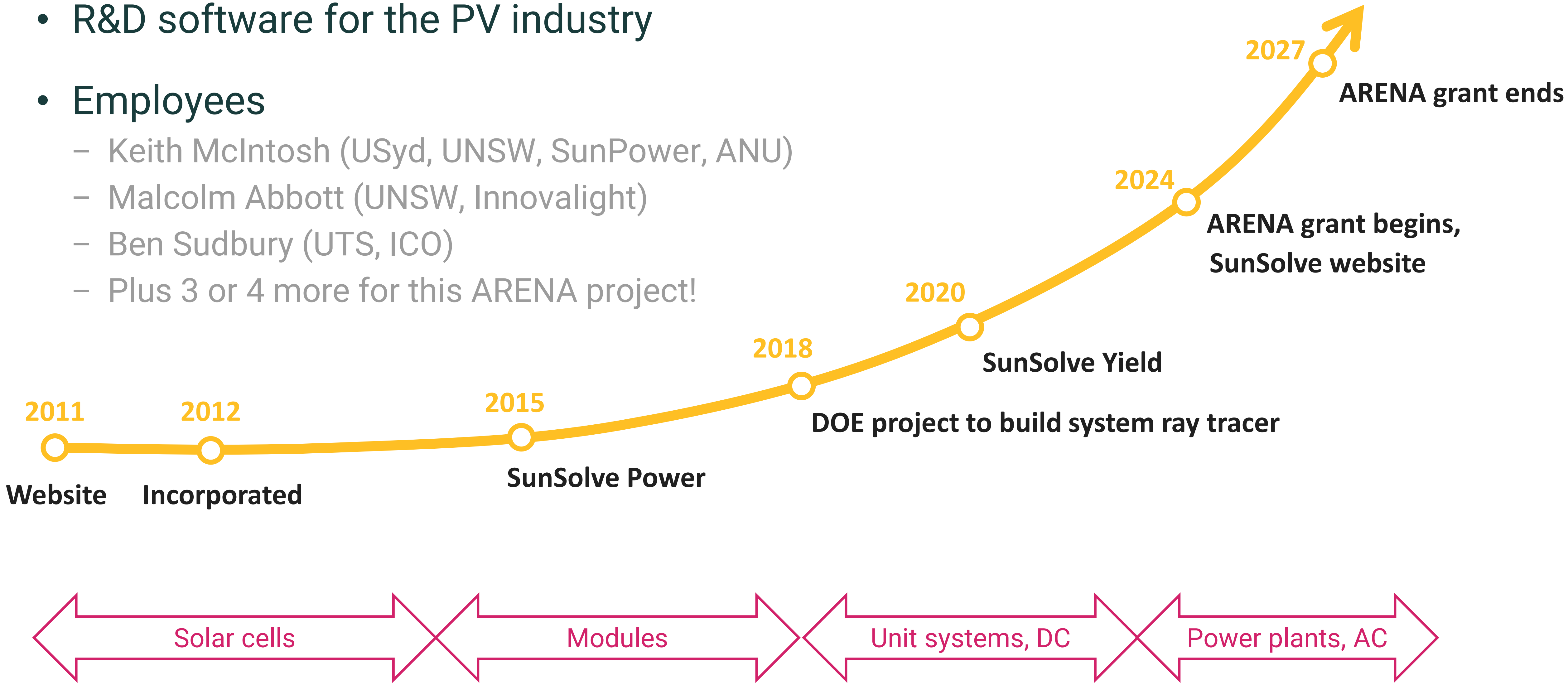
- 3.94M AUD
  - 1.97M AUD from ARENA
  - 1.97M AUD in-kind from PVL
  - In-kind includes providing SunSolve to ACAP members

PV Lighthouse

PV Lighthouse

SunSolve

- R&D software for the PV industry
- Employees
  - Keith McIntosh (USyd, UNSW, SunPower, ANU)
  - Malcolm Abbott (UNSW, Innovalight)
  - Ben Sudbury (UTS, ICO)
  - Plus 3 or 4 more for this ARENA project!



SunSolve

www.sunsolve.info

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When accuracy matters.
Trust SunSolve.

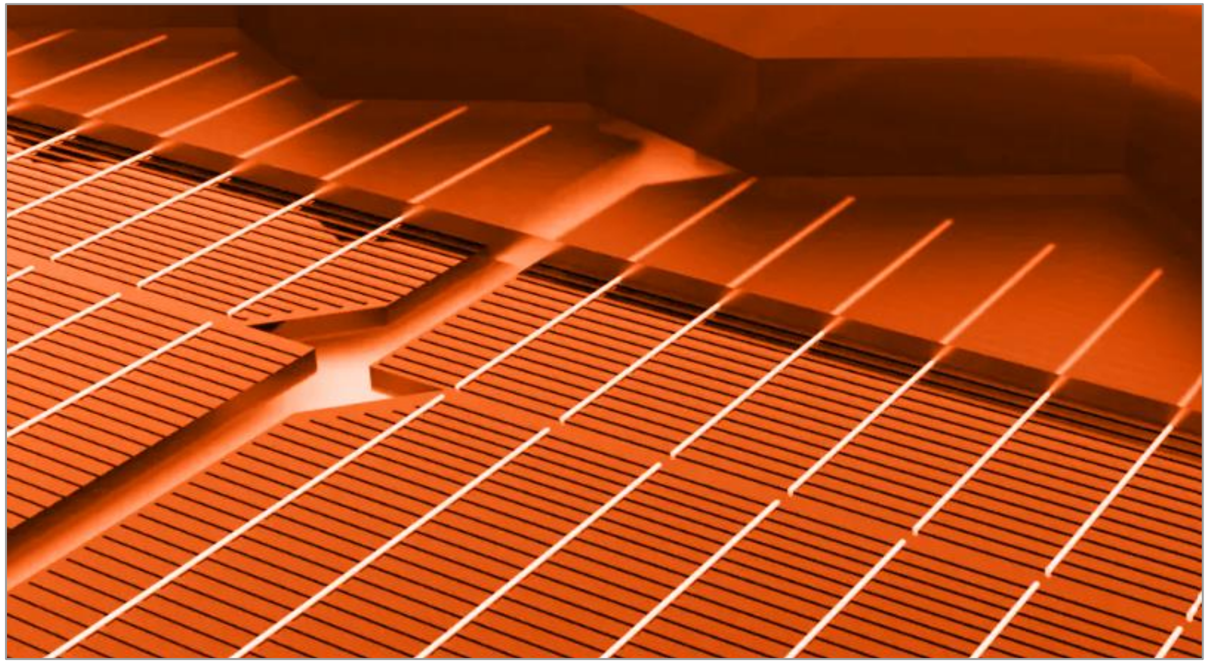
SunSolve is the only simulation environment that models the physics from solar cell right through to annual yield.

SunSolve for: Utility-Scale Solar | Cell and Module Research | Bifacial Factors | Students

SunSolve — products

SunSolve

SunSolve Power



SunSolve Yield

SunSolve — typical users

SunSolve

SunSolve Power

- Cell & module manufacturers
  - SunSolve subscribers shipped 50% of all modules in 2023
- Academic institutes
  - Over 100 academic papers use SunSolve Power

SunSolve Yield

- Developers
  - 11 of the top 35 developers have used SunSolve simulations
- Tracking companies
  - 5 of the biggest tracking companies
- Independent engineering firms
- Module manufacturers

SunSolve — what they solve

SunSolve

SunSolve Power

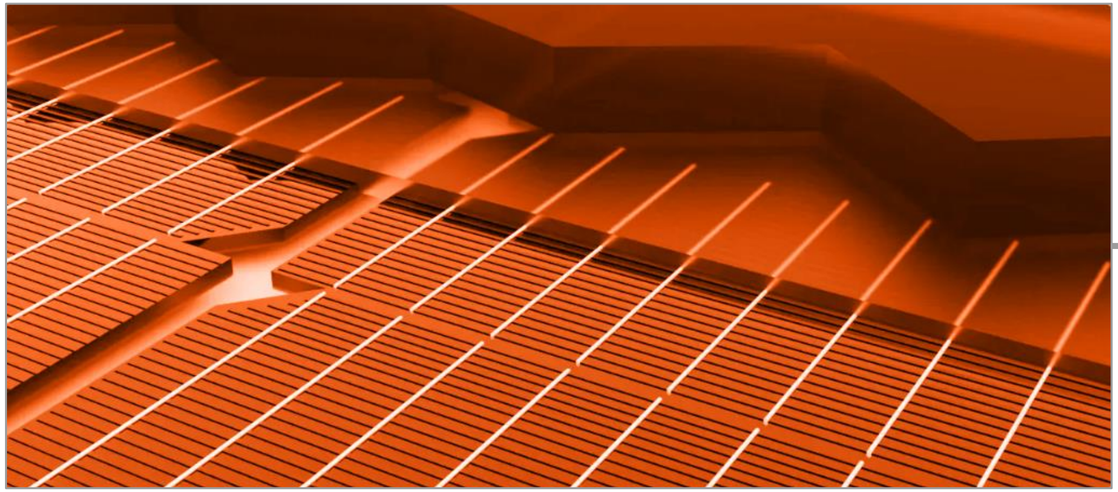
- Wafers, cells, modules, & basic unit systems
- Output power at a single point in time
- Losses in every component vs λ

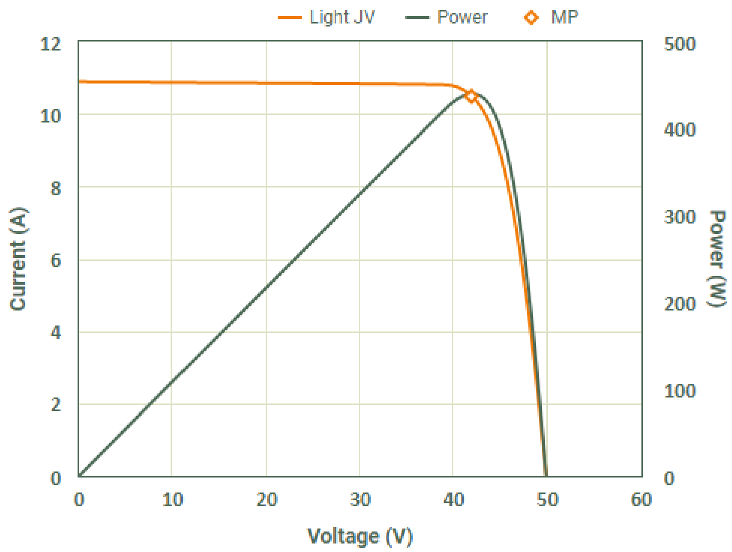
SunSolve Yield

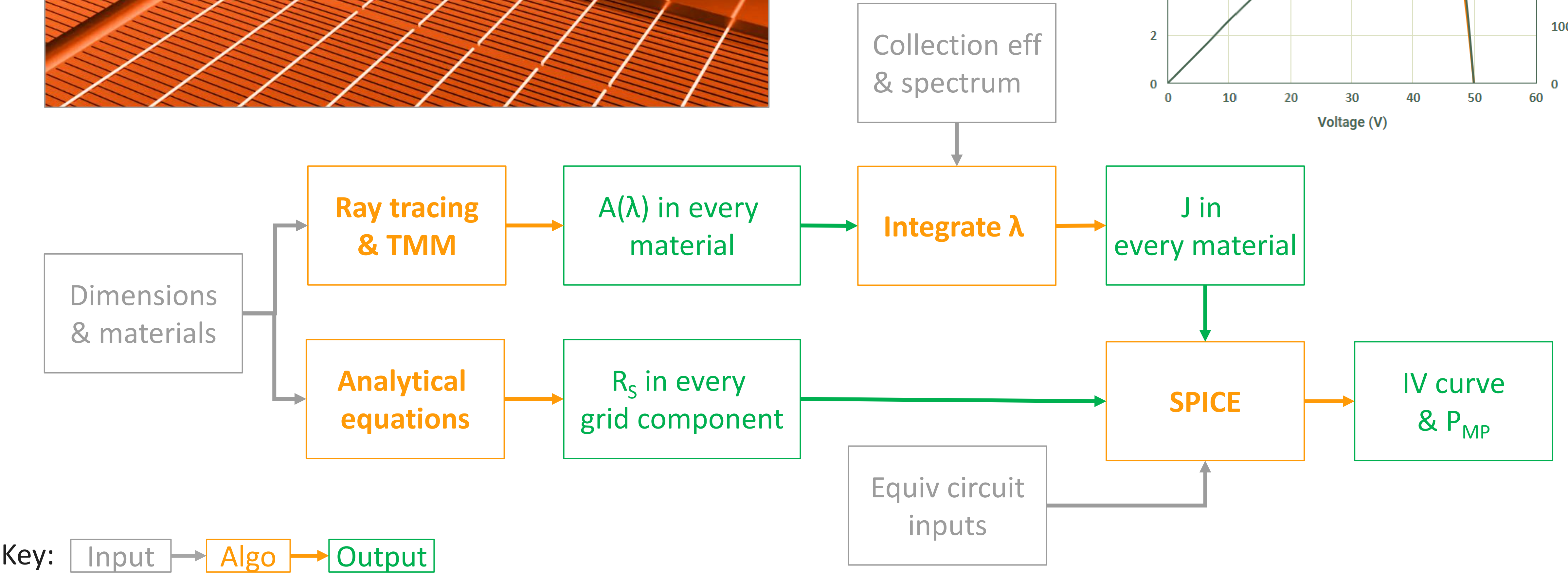
- Detailed unit systems for utility-scale projects
- Output energy over a period of time (e.g., 1 yr)
- Major losses vs time

SunSolve Power — methodology

SunSolve







SunSolve Power — capabilities

SunSolve

Cell structures

- Conventional, Topcon, HJT
- CdTe, CIGS, a-Si, perovskites
- Tandems, multi-junctions

Outputs

- A(λ) in every material
- R(λ, θ) and T(λ , θ)
- R_S of each component
- EQE(λ)
- IV curve
- Mismatch loss
- G(z) in substrate and films
- Colour

Features

- Any number of films & layers
- Non-uniform film thickness
- Effective media

- Pyramids/V-grooves/isotexture
- Texture-on-texture

- Scattering
- Backsheet reflection

- Cell shapes and layouts
- Grid patterns and finger cross sections
- Bypass diodes

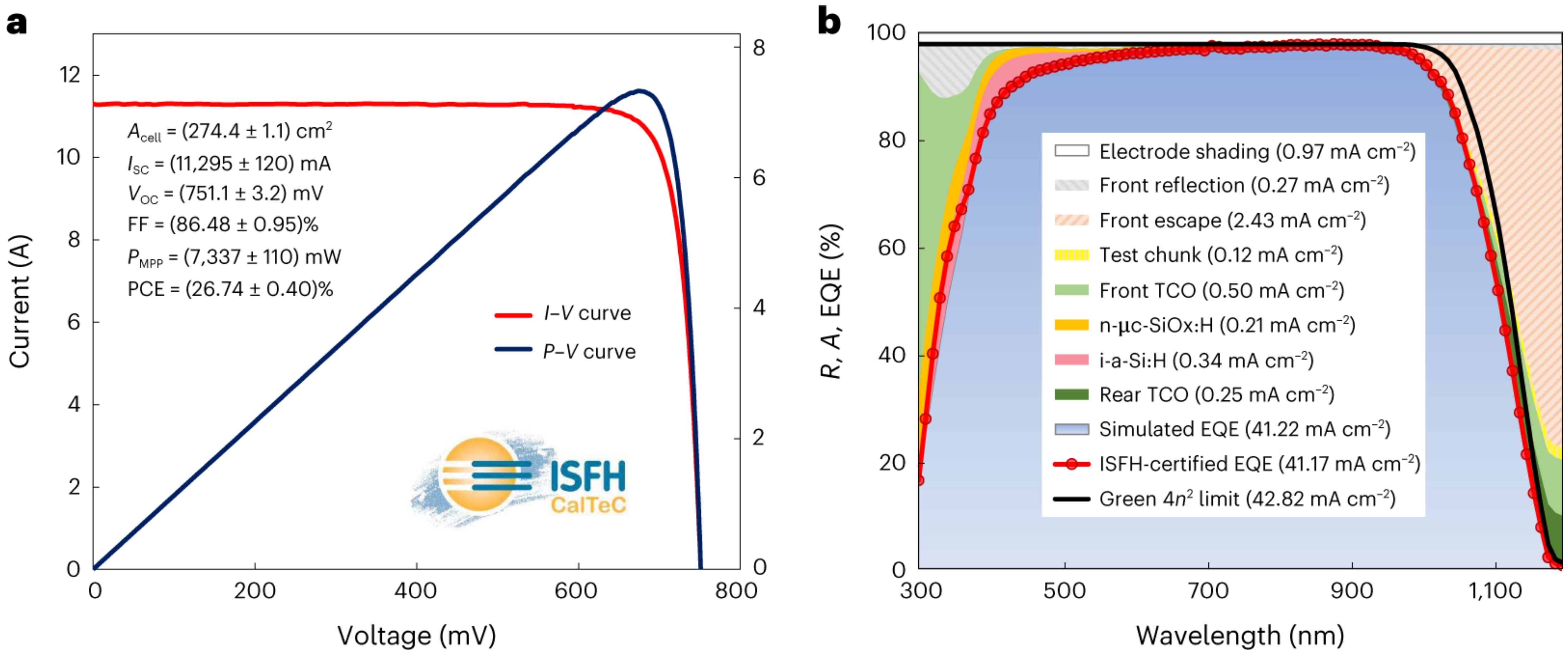
- Free-carrier absorption

- Many illumination options

SunSolve Power — examples

SunSolve

- Loss analysis of world-record SHJ solar cells by Longi (26.74%)

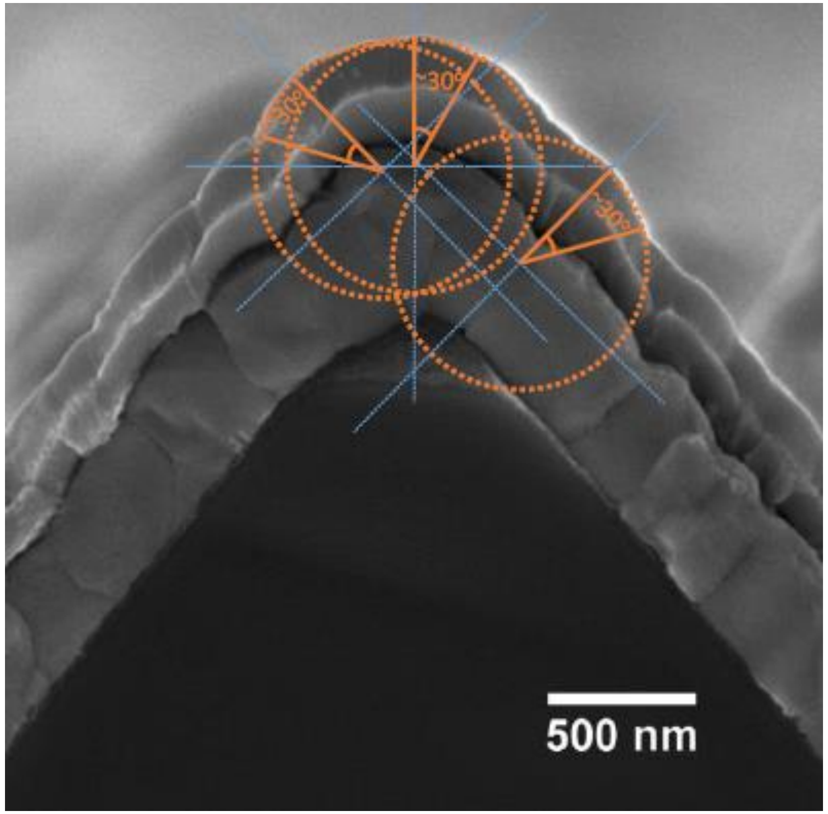


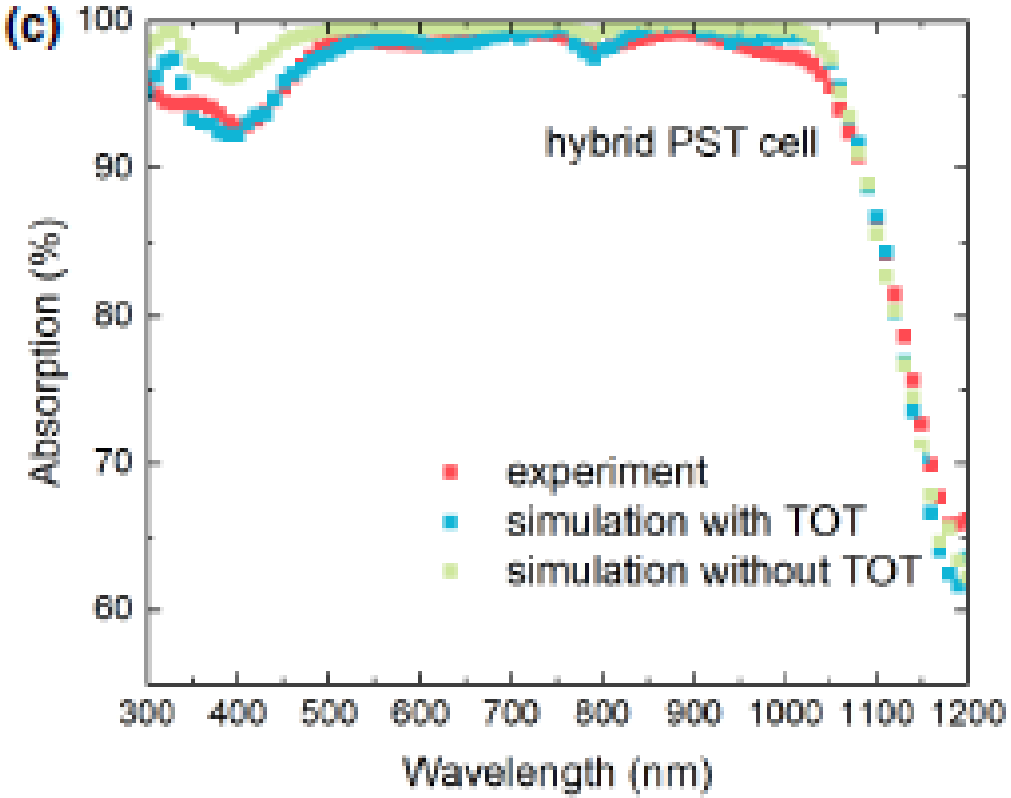
H. Lin et al. *Nature Energy* **8**, 789–799, 2023.

SunSolve Power — examples

SunSolve

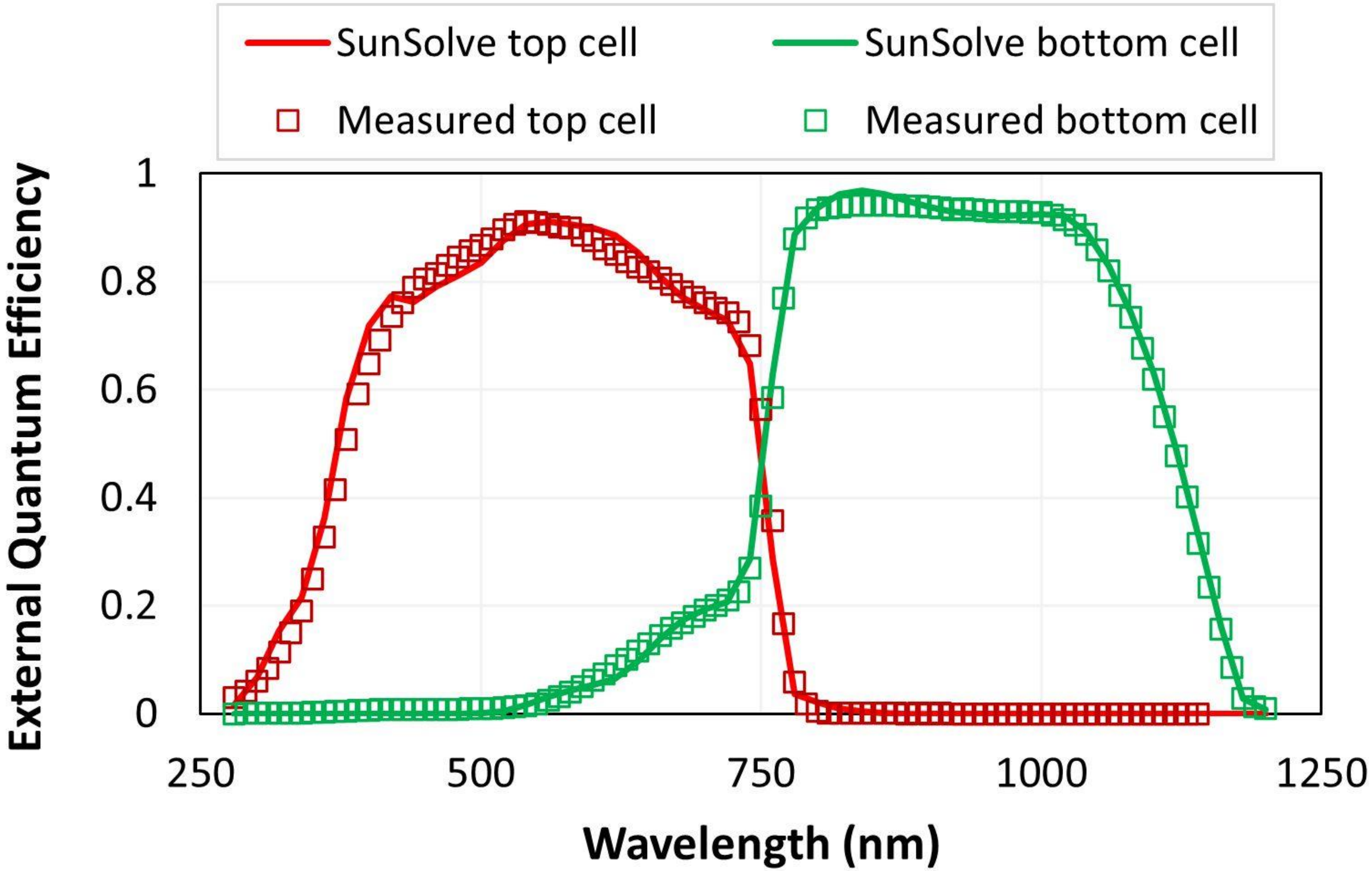
- Optical analysis of perovskite–silicon tandems by KAUST





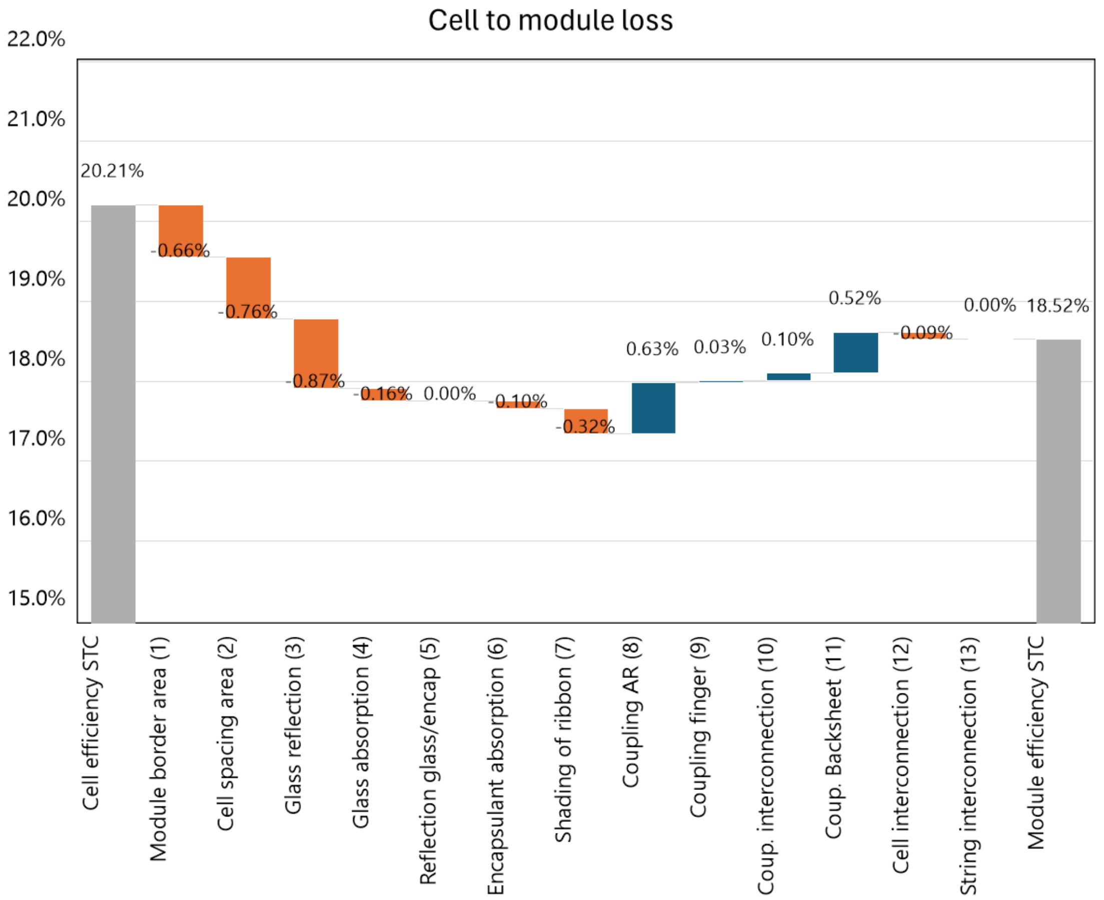
L. Xue et al. *PRX Energy* **1**, 023005, 2022.

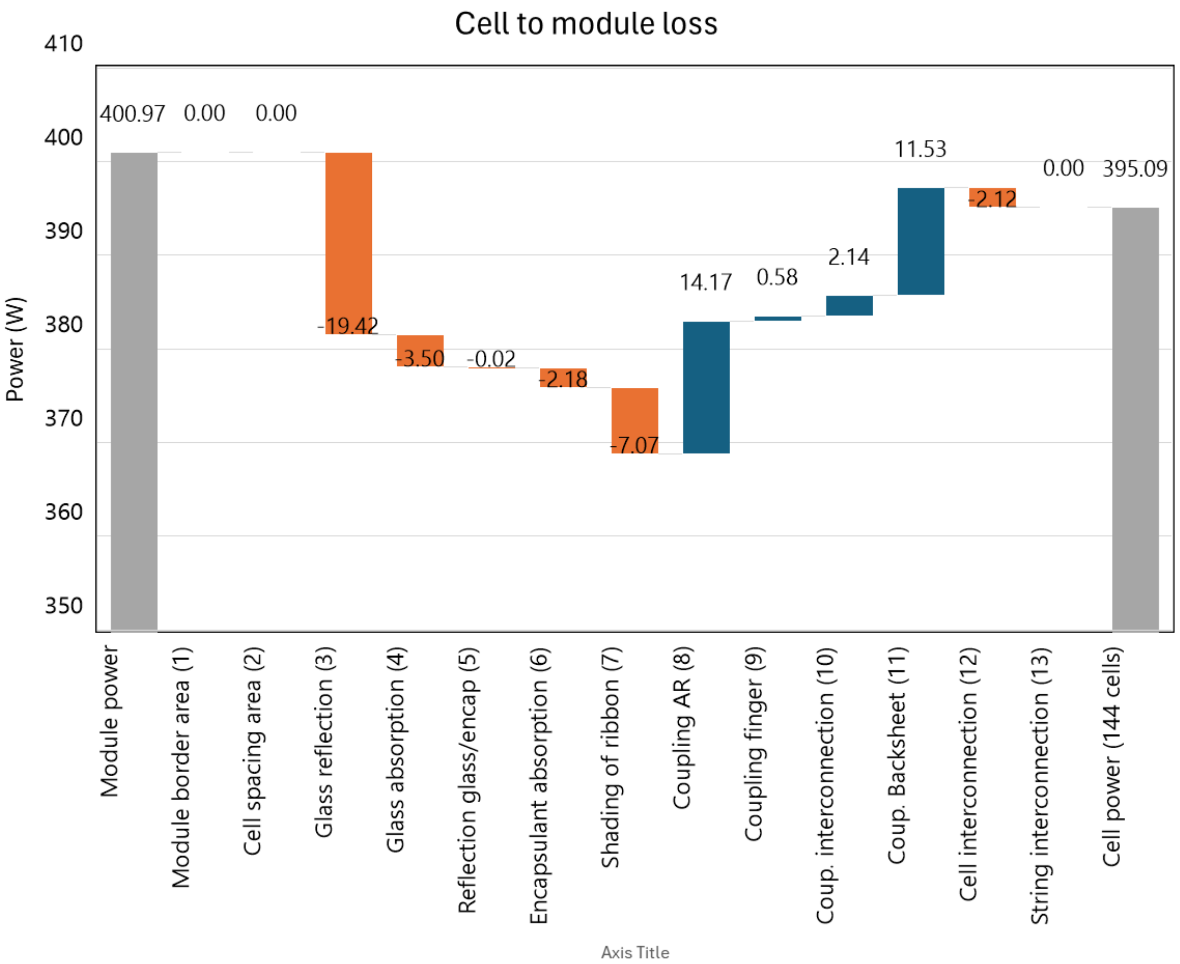
SunSolve Power — examples



Fitting tandem cell data received from KAUST.

SunSolve Power — examples





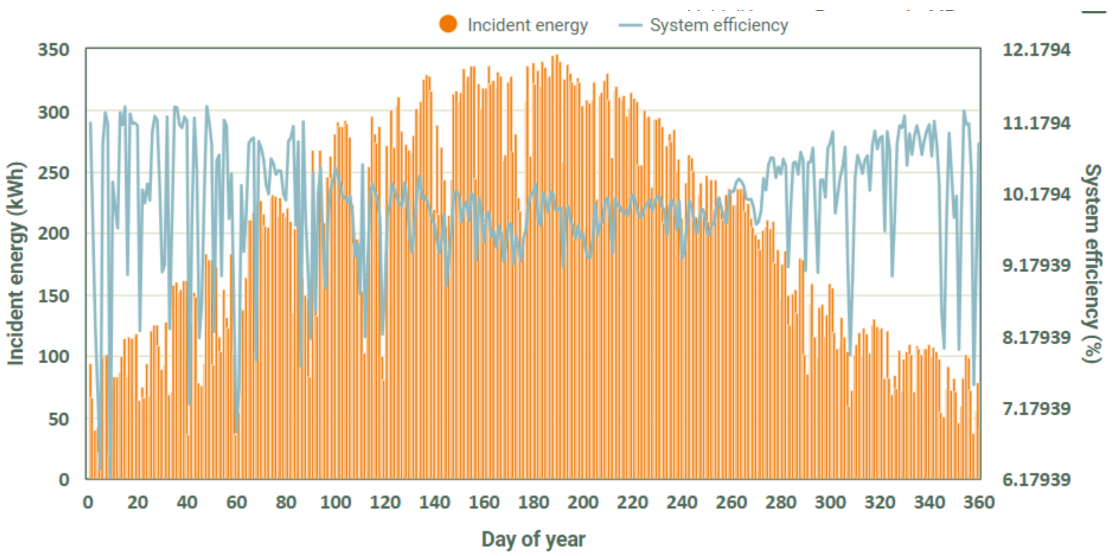
CTM following approach of I. Haedrich et al. *Solar Energy Materials & Solar Cells* **131**, 14–23 , 2014.

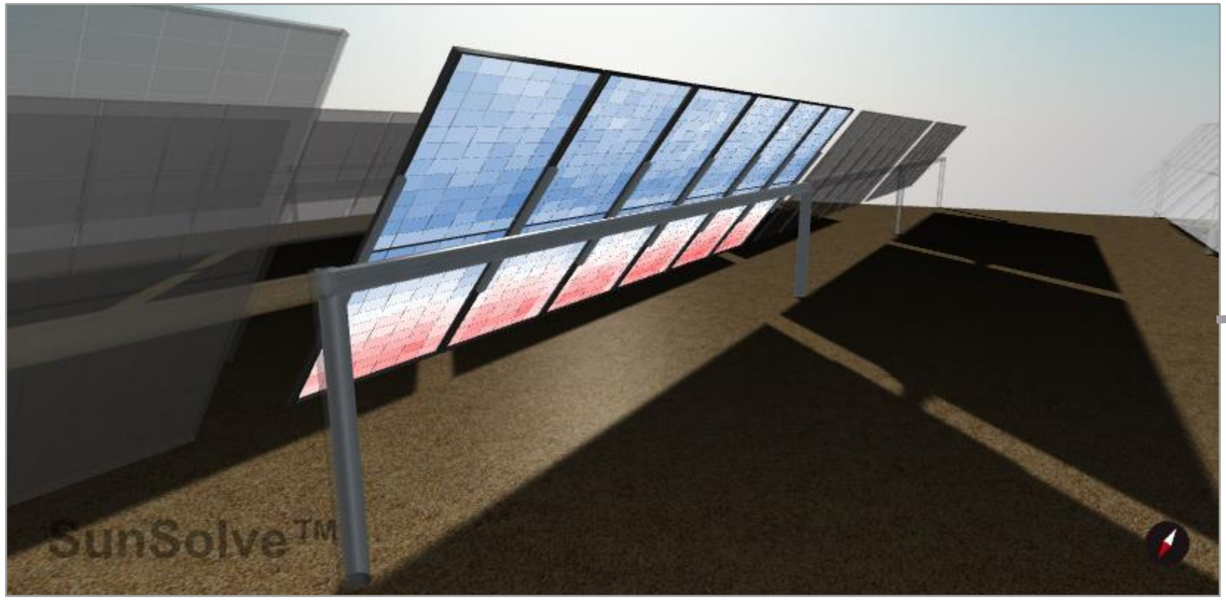
SunSolve Power — applications

SunSolve

- Optimisation
- Loss analysis
- Cell-to-module losses (CTM)
- Material evaluation
- Evaluate experimental measurements
- Sensitivity studies
- Quantify immeasurables
  - Light trapping
  - Cell-to-cell mismatch
- Colour
- Education

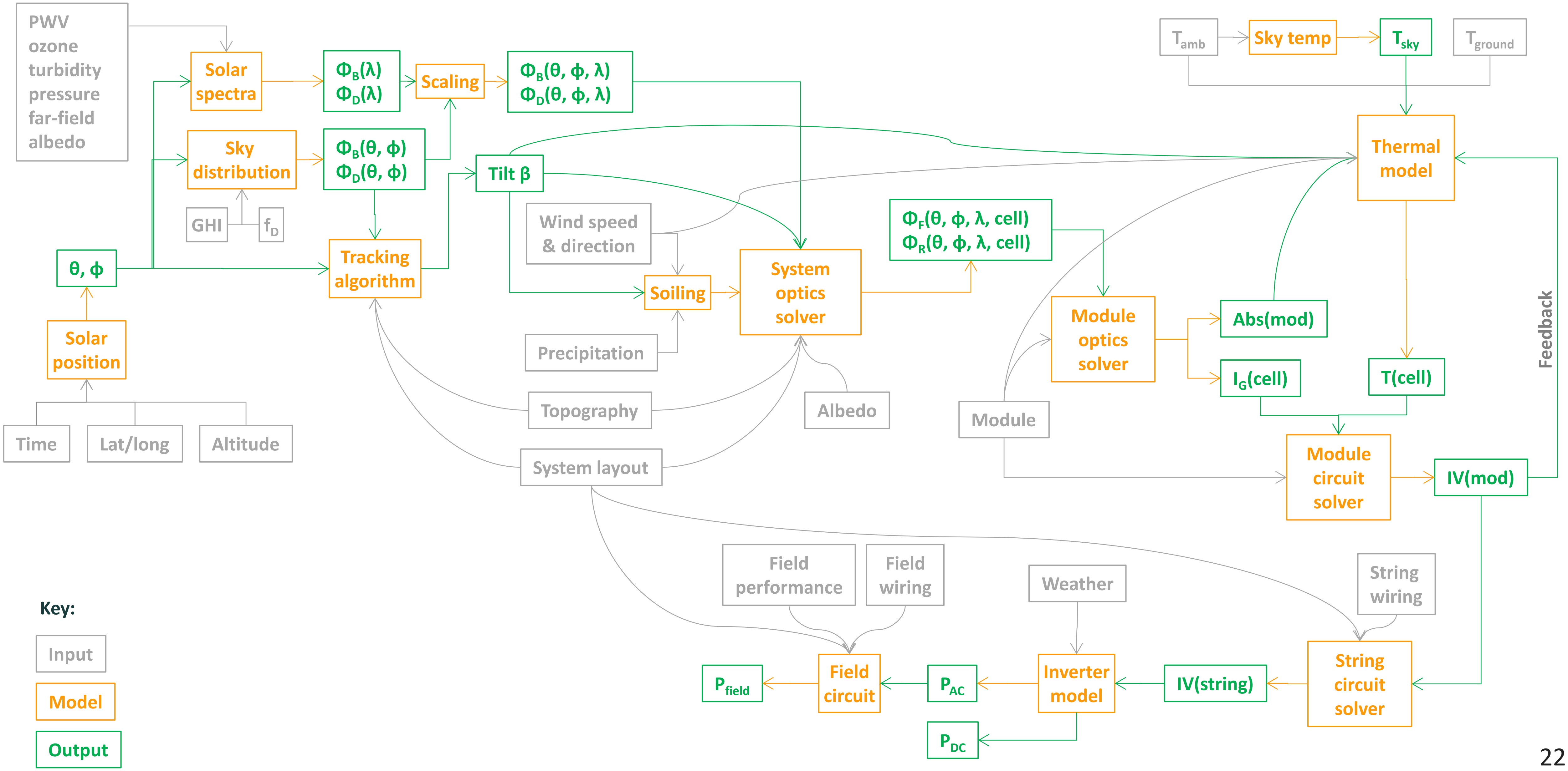
SunSolve Yield – methodology





SunSolve Yield — methodology

SunSolve



SunSolve Yield — capabilities

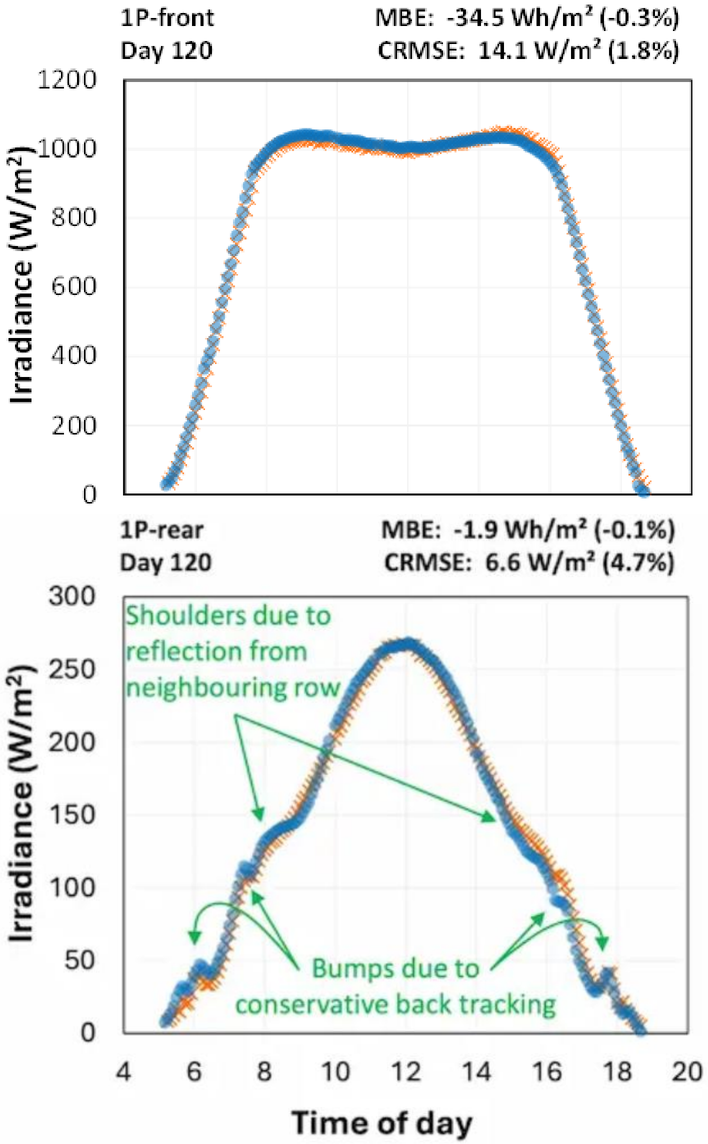
SunSolve

- Any location (lat & long)
- Any weather
  - Direct & diffuse light
  - Wind speed & direction
  - Ambient temperature
  - Atmospheric conditions
- Tracking, fixed, waves (like 5B), ad hoc
- Complex modules (as in SunSolve Power)
- Simple modules (as in PVSyst)
- Si, CdTe, emerging technologies
- Monofacial & bifacial
- Module layout and height, row pitch
- Module stringing
- Inverter behaviour
- Albedo
  - Spatially variable
  - Wavelength dependent
- Structural supports
  - Posts
  - Torque tube, rafters, purlins
  - Clamps, module frames
  - Custom objects
- Yield – annual, daily, hourly
- I_{SC} of every cell (front and rear)
- P_{MP}, I_{MP}, V_{MP} of each module
- DC or AC
- Mismatch loss (cell-to-cell, mod-to-mod)
- 5, 15, 30, 60 min time steps
- API

SunSolve Yield — irradiance

SunSolve

Orange: measured   Blue: SunSolve sims



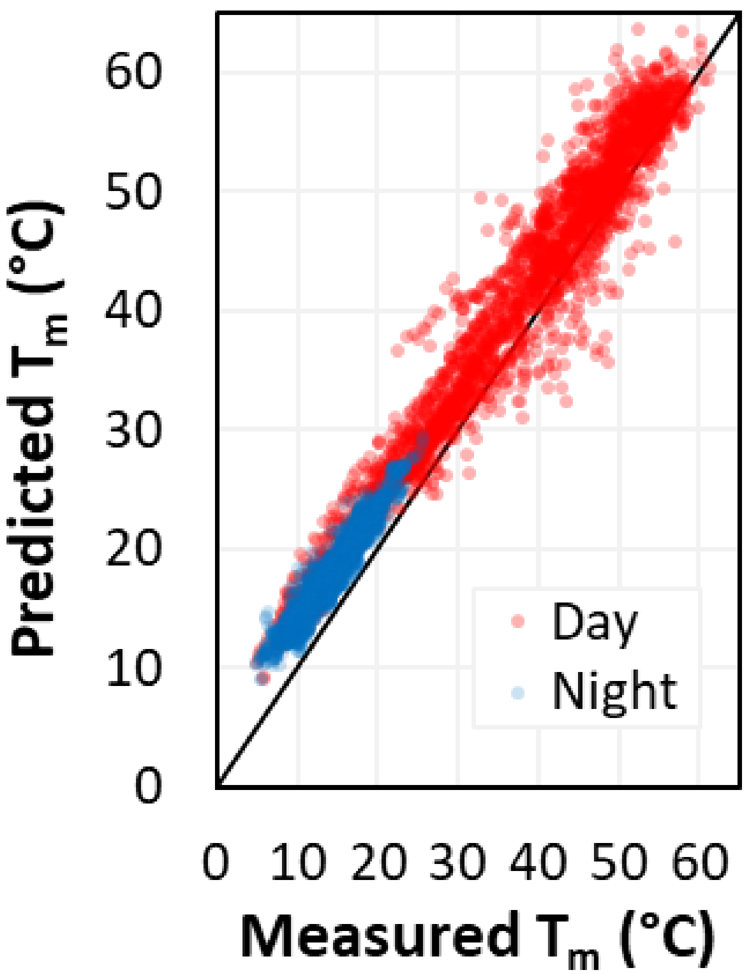
K.R. McIntosh *et al.*, "Differences between advanced and conventional models in bifacial yield simulations," PVPMC workshop, Salt Lake City, 2023.

SunSolve Yield — module temperature

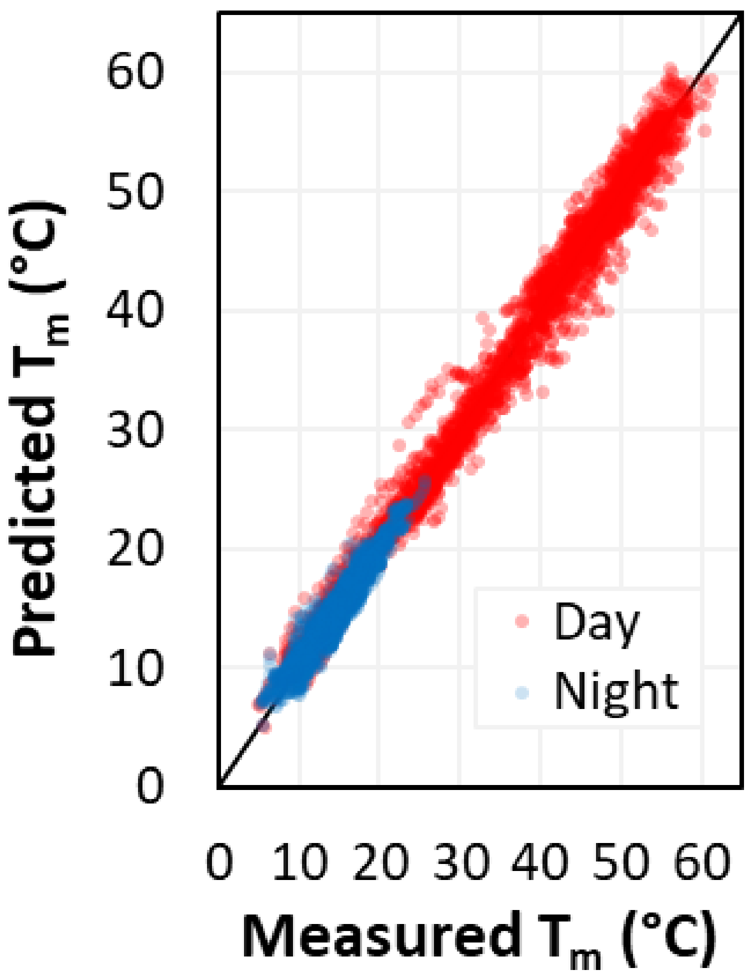
SunSolve

Temperature measured by TCs

Standard temperature model



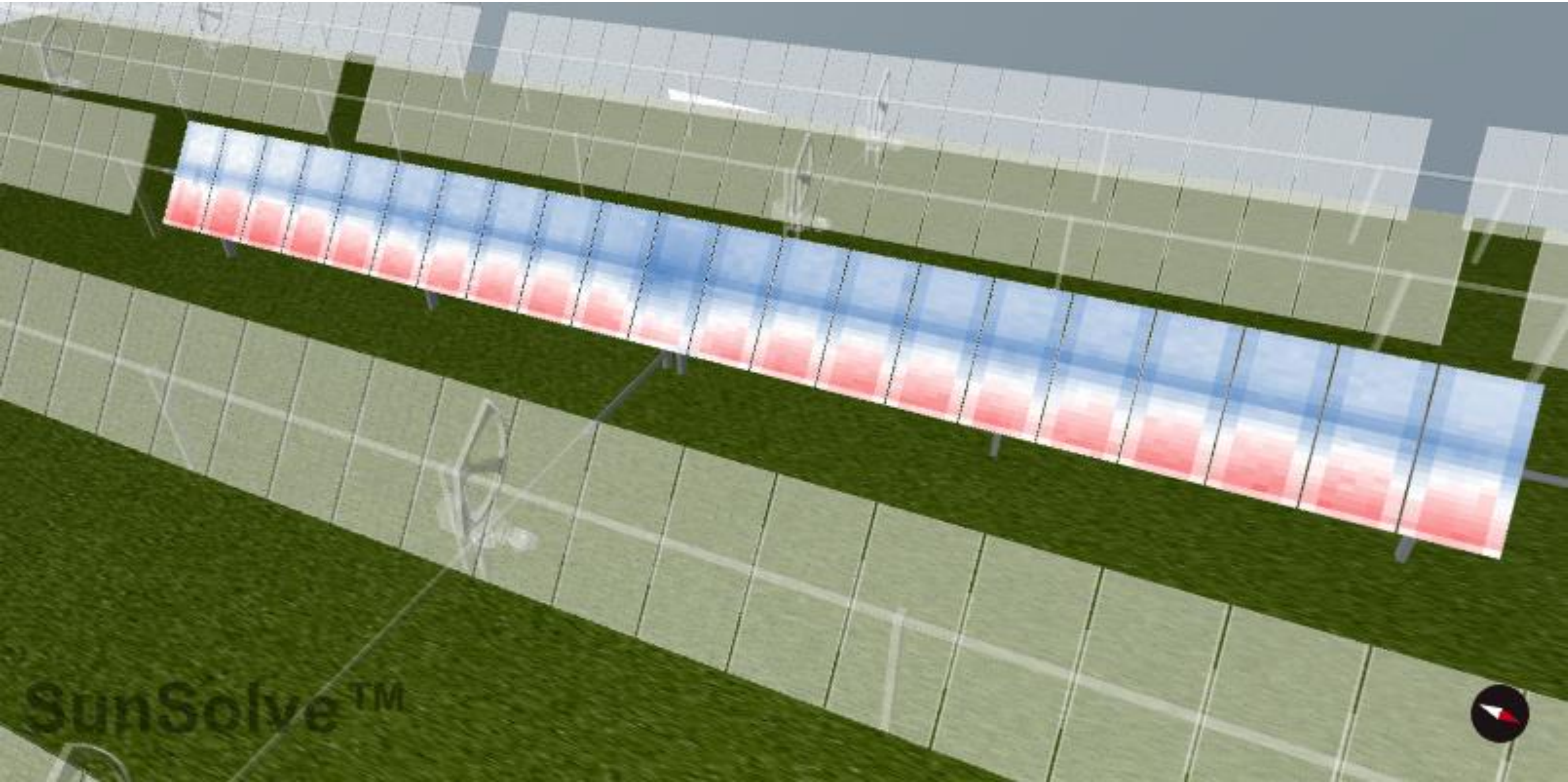
Advanced temperature model



K.R. McIntosh et al., "The influence of wind and module tilt on the operating temperature of single-axis trackers," *49th IEEE PVSC*, 2022.

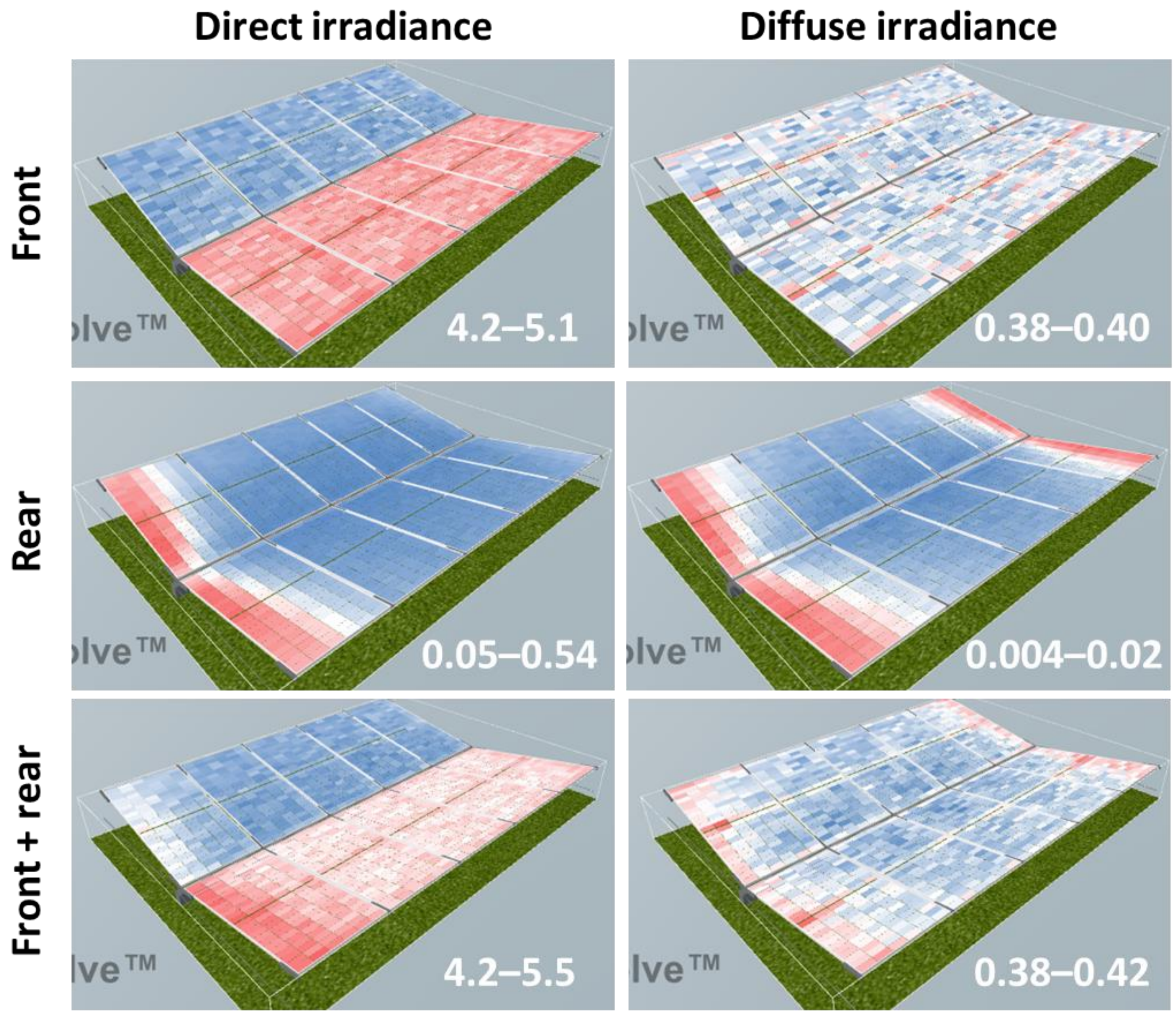
SunSolve Yield — rear shading

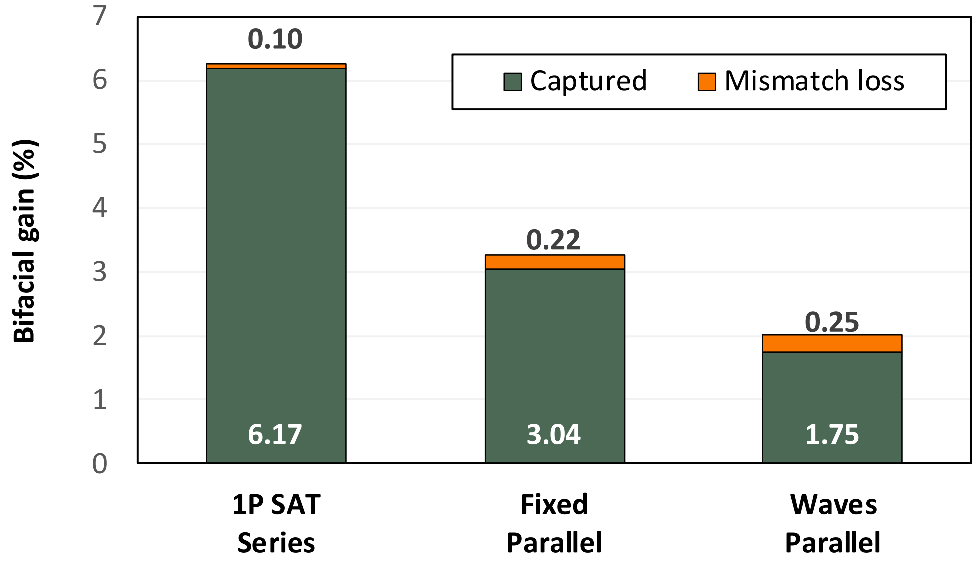
SunSolve



SunSolve Yield — bifacial gain & mismatch

SunSolve

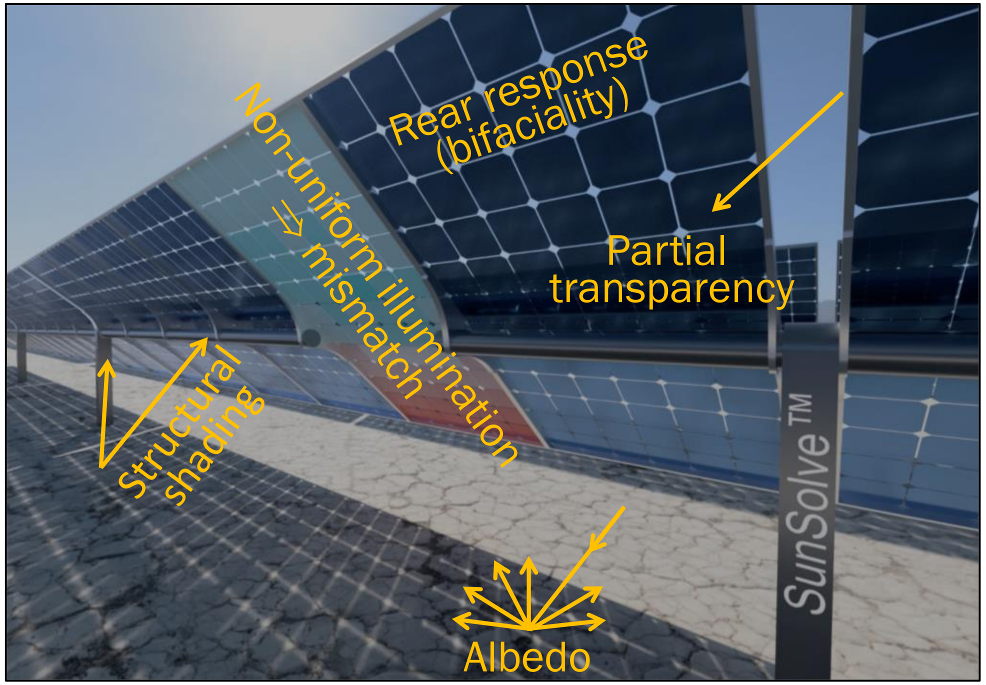




K.R. McIntosh et al., *40th EU PVSEC*, 2023.

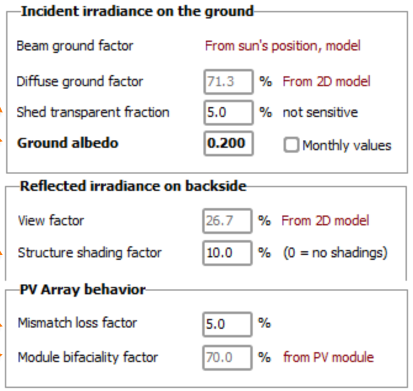
SunSolve Yield — extract PVSyst factors

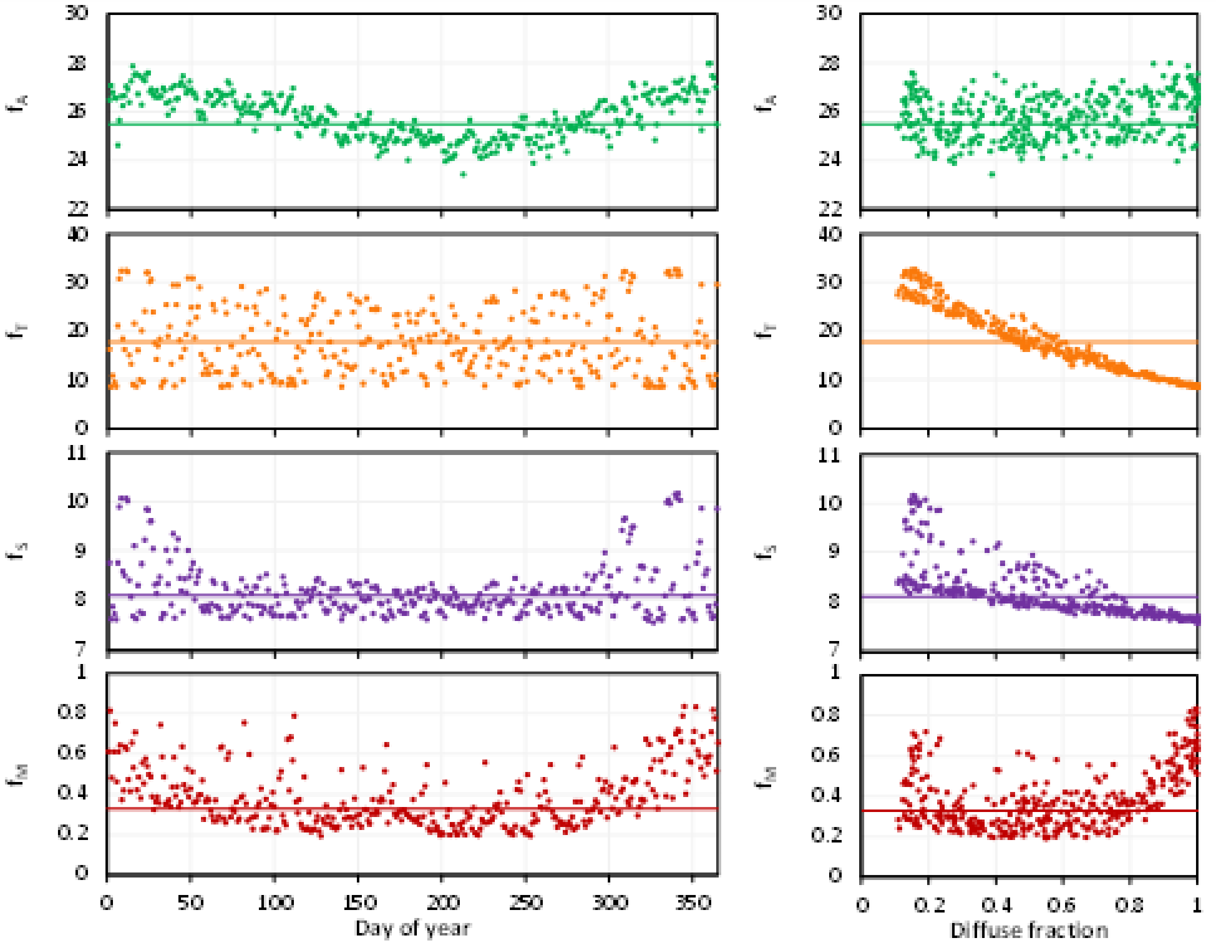
SunSolve



Factor	Symbol	Represents
Transmission	f_T	Light passing between or through modules.
Albedo	f_A	Ground reflectance.
Structural shading	f_S	Shading from torque-tube, posts, clamps, etc.
Rear mismatch	f_{MR}	Reduction in the extra power arising from rear illumination due to cell-to-cell mismatch.
Bifaciality	f_B	Module response to rear illum relative to front illum.

Bifacial system definition tab in PVSyst

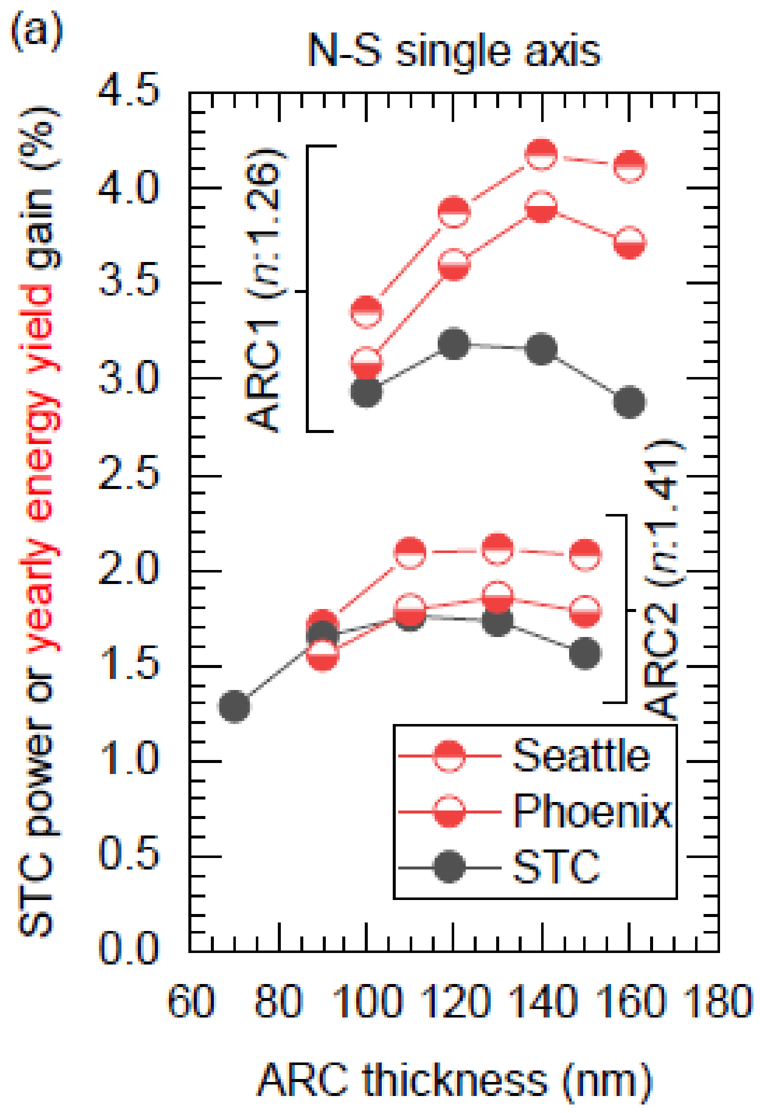




PV Lighthouse white paper on determining PVSyst factors

SunSolve Yield — ARC optimisation

SunSolve



Z.J. Yu et al., "Design of antireflection coating on PV module glass for maximum energy yield," *IEEE PVSC*, 2022.

SunSolve Yield — main applications

SunSolve

- Annual yield
- Test new structural designs (e.g., Trackers, Mavericks, purlins, rafters, etc.)
- Quantify
  - Bifacial gain
  - Shading loss
  - Edge brightening
  - Spectral correction
  - Electrical mismatch
- Sensitivity analysis
- Determine PVSyst factors
- Optimise modules for real-world conditions
- Education

Research opportunities

Research opportunities

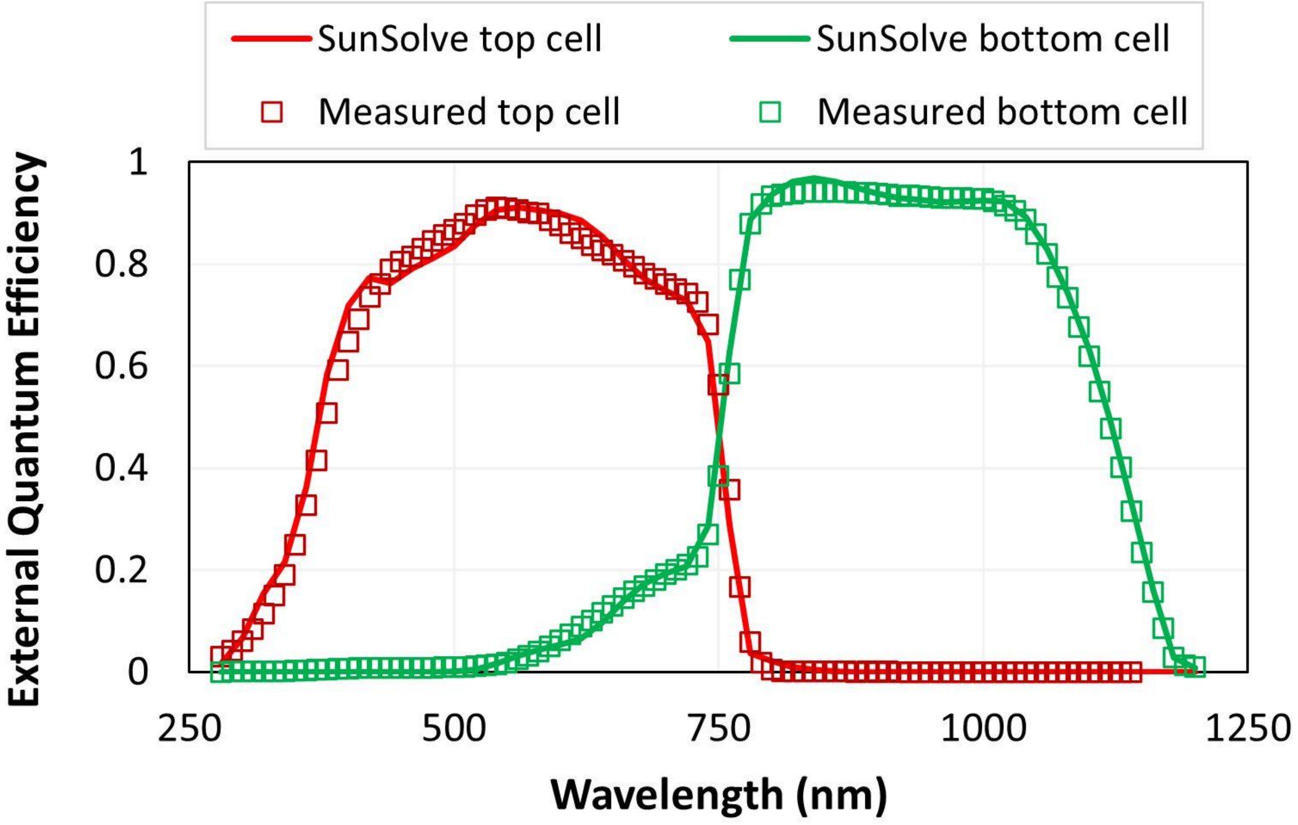
SunSolve

- Three-year subscriptions
  - SunSolve Power
  - SunSolve Yield
- ACAP partners
  - ANU
  - CSIRO
  - Macquarie
  - Monash
  - University of Melbourne
  - UNSW
  - UQ
  - USyd
- NB: SunSolve results cannot be shared with third parties unless
  - The results have been published
  - The third party is already a subscriber
- SunSolve users are welcome to send PVL
  - Bug reports
  - Discrepancies with experiment
  - Drafts of papers that use SunSolve

Research opportunities — tandems

SunSolve

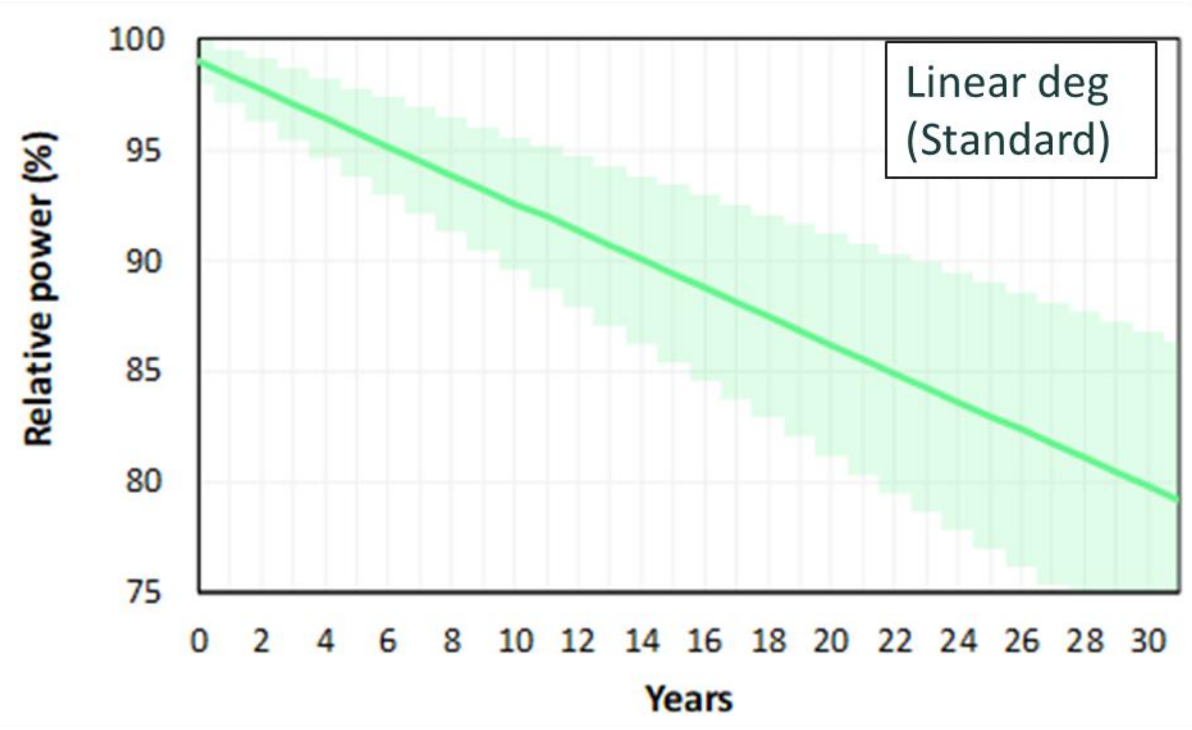
- Texture
- Optical dependence on temperature
- Coupling
- Spectral mismatch
- Optimisation for
  - STC
  - Real world
- IV parameters

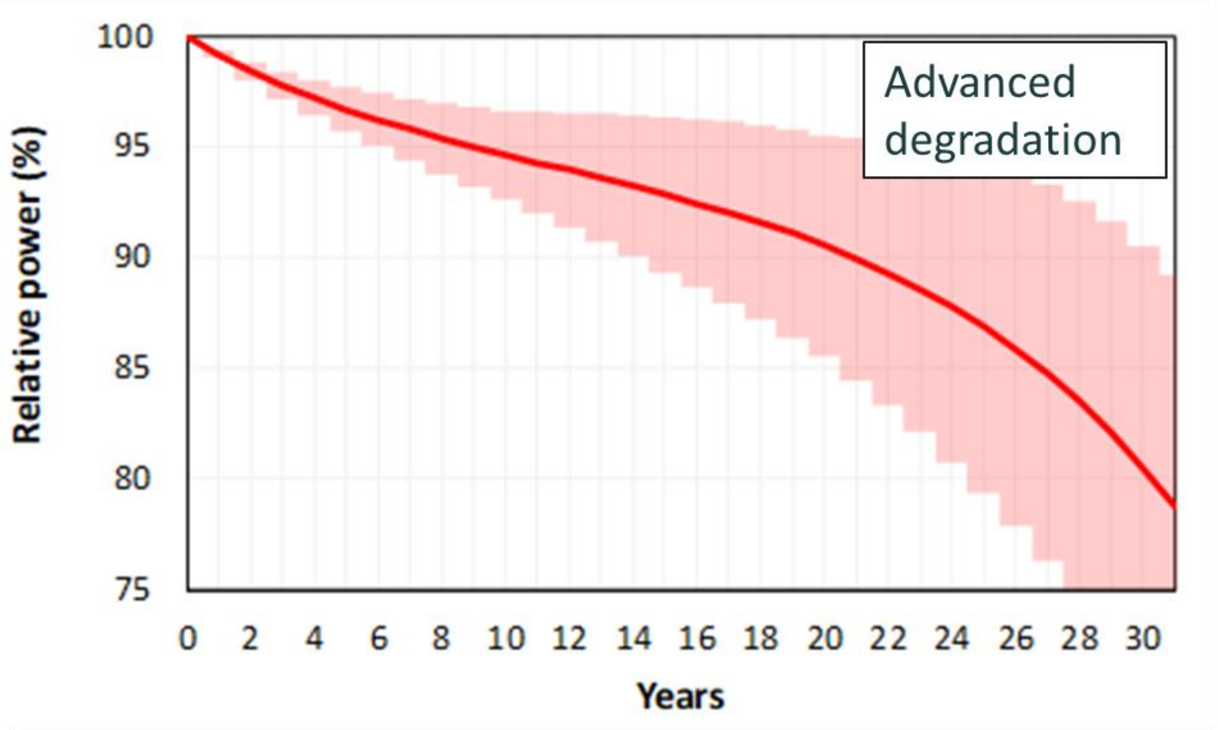


Research opportunities — degradation

SunSolve

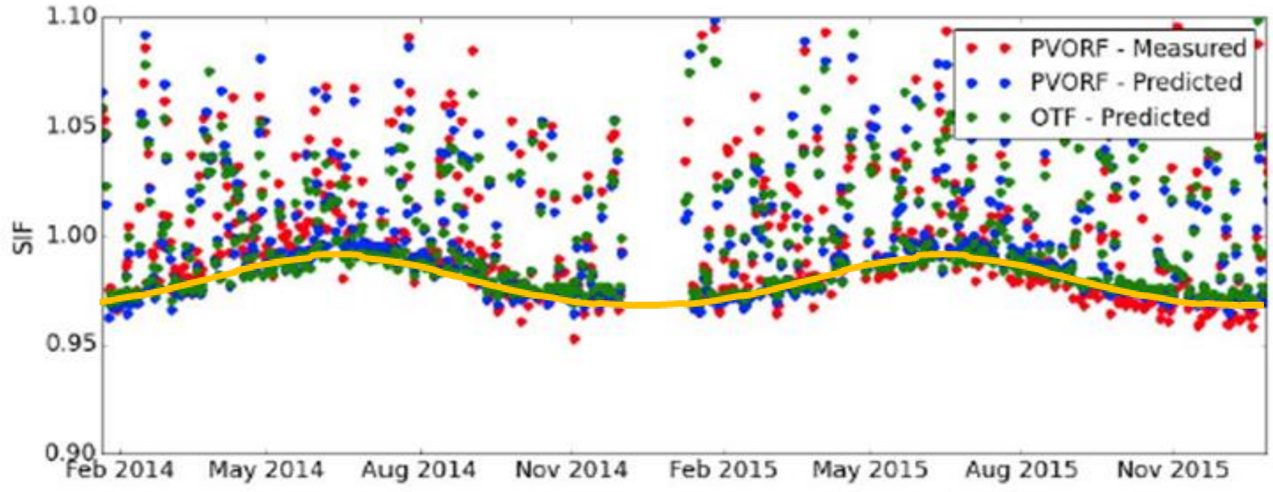
- Degradation models
  - Dependent on weather
  - Dependent on operating condition
  - Non-linear



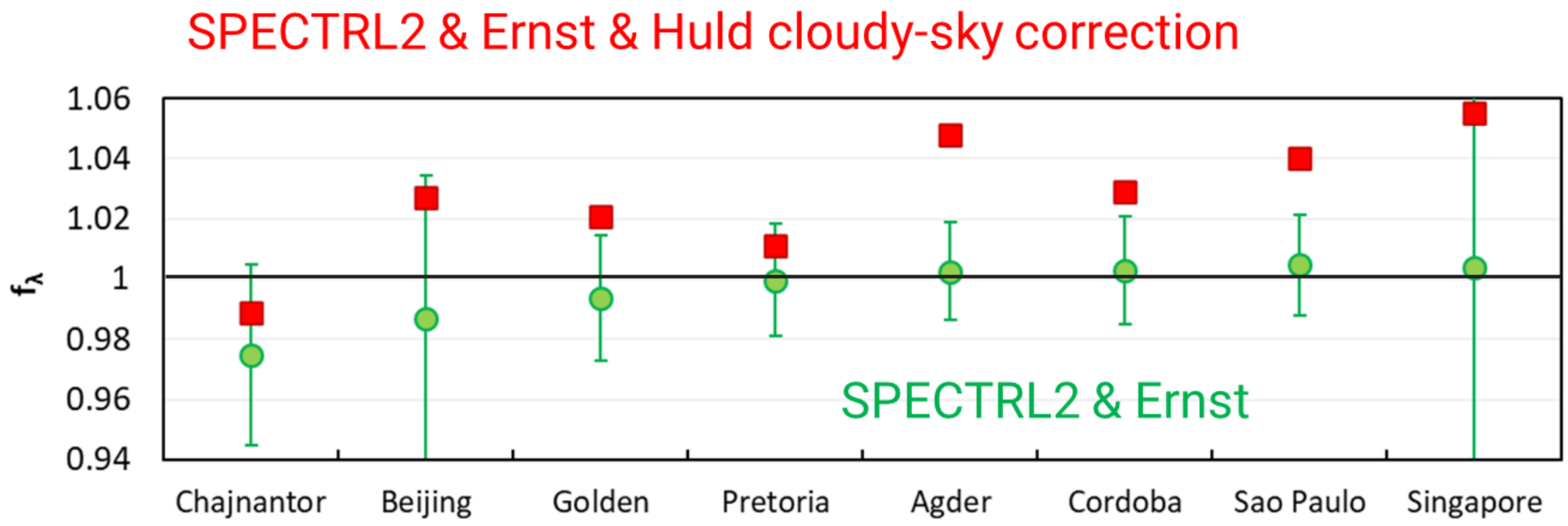


Research opportunities — cloudy spectra

SunSolve



B.C. Duck and C.J. Fell, "Improving the spectral correction function," 43rd IEEE PVSC, pp. 2647-2652, 2016.



K.R. McIntosh et al., "The uncertainty in yield forecasts due to the ever-changing solar spectrum," *PVPMC*, 2024.

Research opportunities — thermal

SunSolve

- Faiman model

$$dT_m/dt = 0 \rightarrow Q_{in} = Q_{out}$$

$$Q_{in} = (POA_F + POA_R) \cdot (\alpha - \eta)$$

$$Q_{out} = Q_a$$

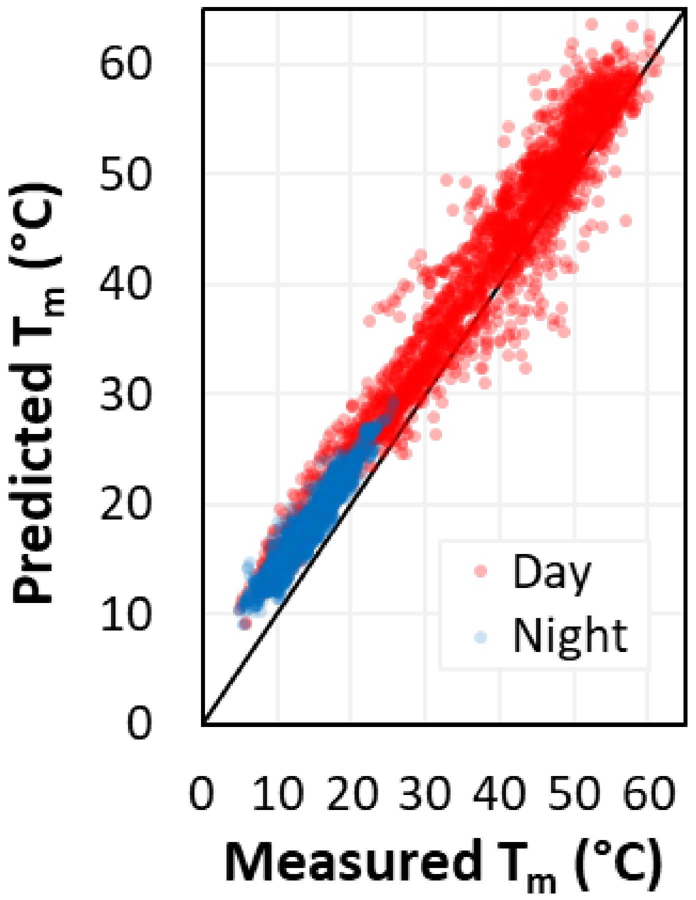
$$Q_a = (U_c + U_v \cdot w) \cdot (T_m - T_a)$$

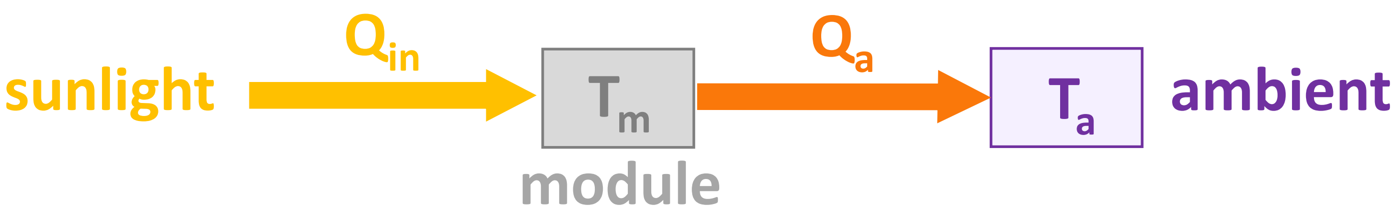
- Common inputs

$U_c = 25$

$U_v = 1.2$

MBE: +3.2 °C
RMSE: 4.5 °C





Research opportunities — thermal

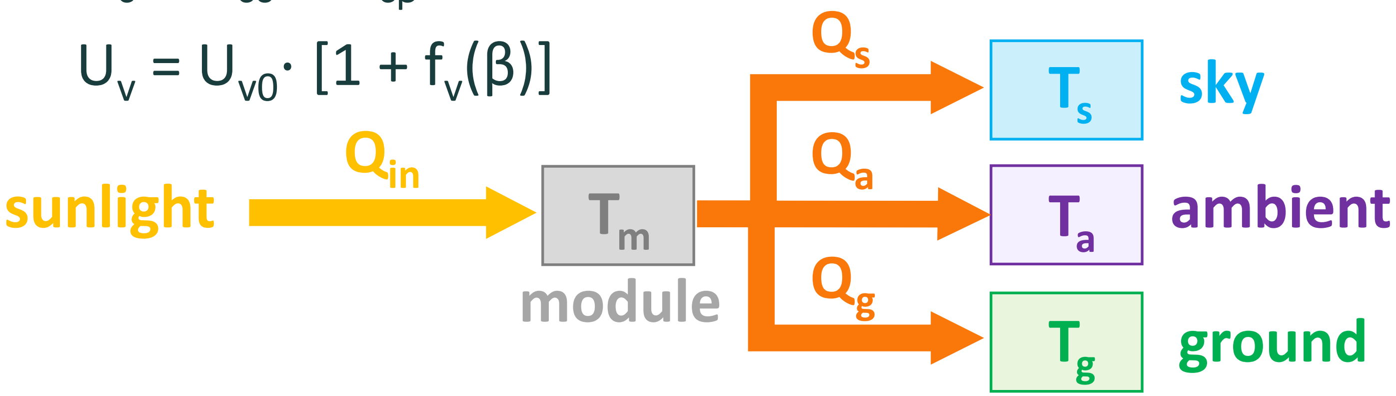
SunSolve

- Add transient & more sinks

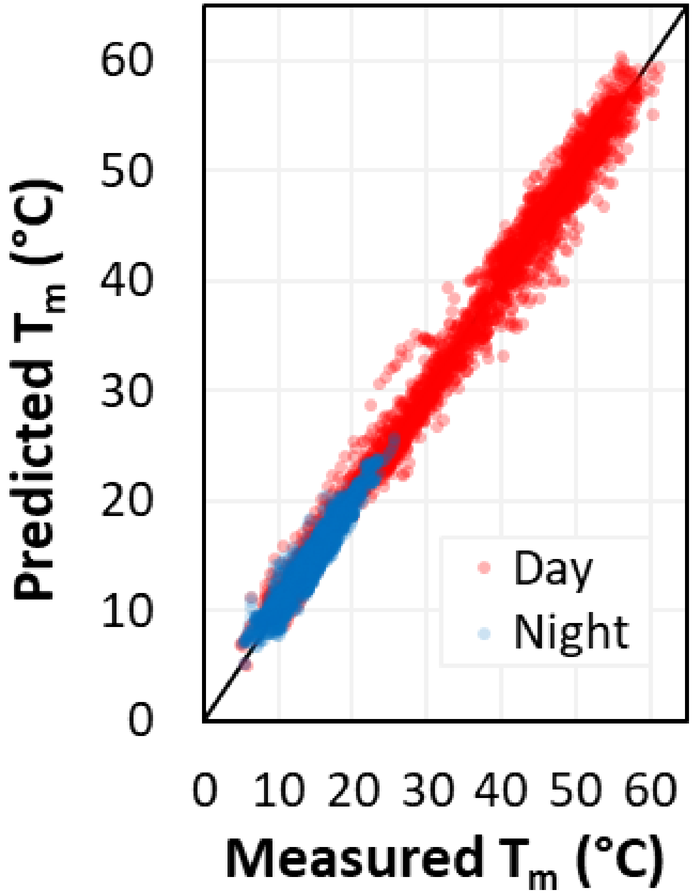
$$dT_m/dt = Q_{in} - Q_{out}$$
$$Q_{in} = (POA_F + POA_R) \cdot (\alpha - \eta)$$
$$Q_{out} = Q_a + Q_s + Q_g$$
$$Q_a = (U_c + U_v \cdot w) \cdot (T_m - T_a)$$
$$Q_s = f_{ms} \cdot \varepsilon \cdot \sigma \cdot (T_m^4 - T_s^4)$$
$$Q_g = U_g \cdot (T_m - T_g)$$
$$U_c = U_{c0} + U_{c\beta} \cdot |\beta|$$
$$U_v = U_{v0} \cdot [1 + f_v(\beta)]$$

- Best-fit everything

$$U_{c0} = 12.4,\ U_{c\beta} = -5.0$$
$$U_{v0} = 2.7$$
$$\varepsilon = 0.88$$
$$T_s = 0.0052 \cdot T_a^{1.5}$$
$$c = 1200$$
$$U_g = 2.5,\ T_g = 13\ °C$$

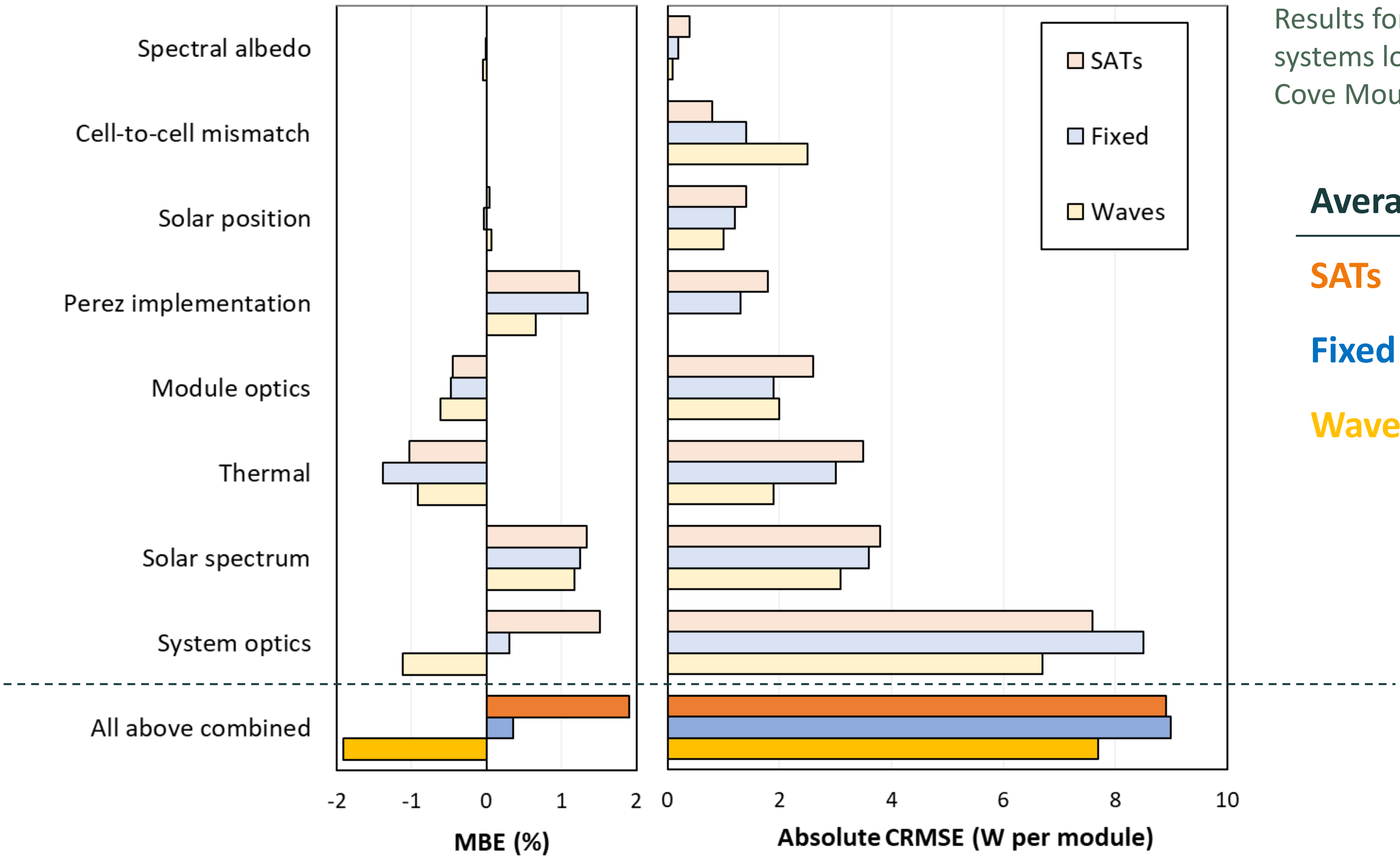


MBE: 0 °C
RMSE: 1.4 °C



Research opportunities

SunSolve



Results for typical systems located at Cove Mountain, UT.

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

K.R. McIntosh et al., "Differences between advanced and conventional models in bifacial yield simulations," *PVPMC*, 2023.

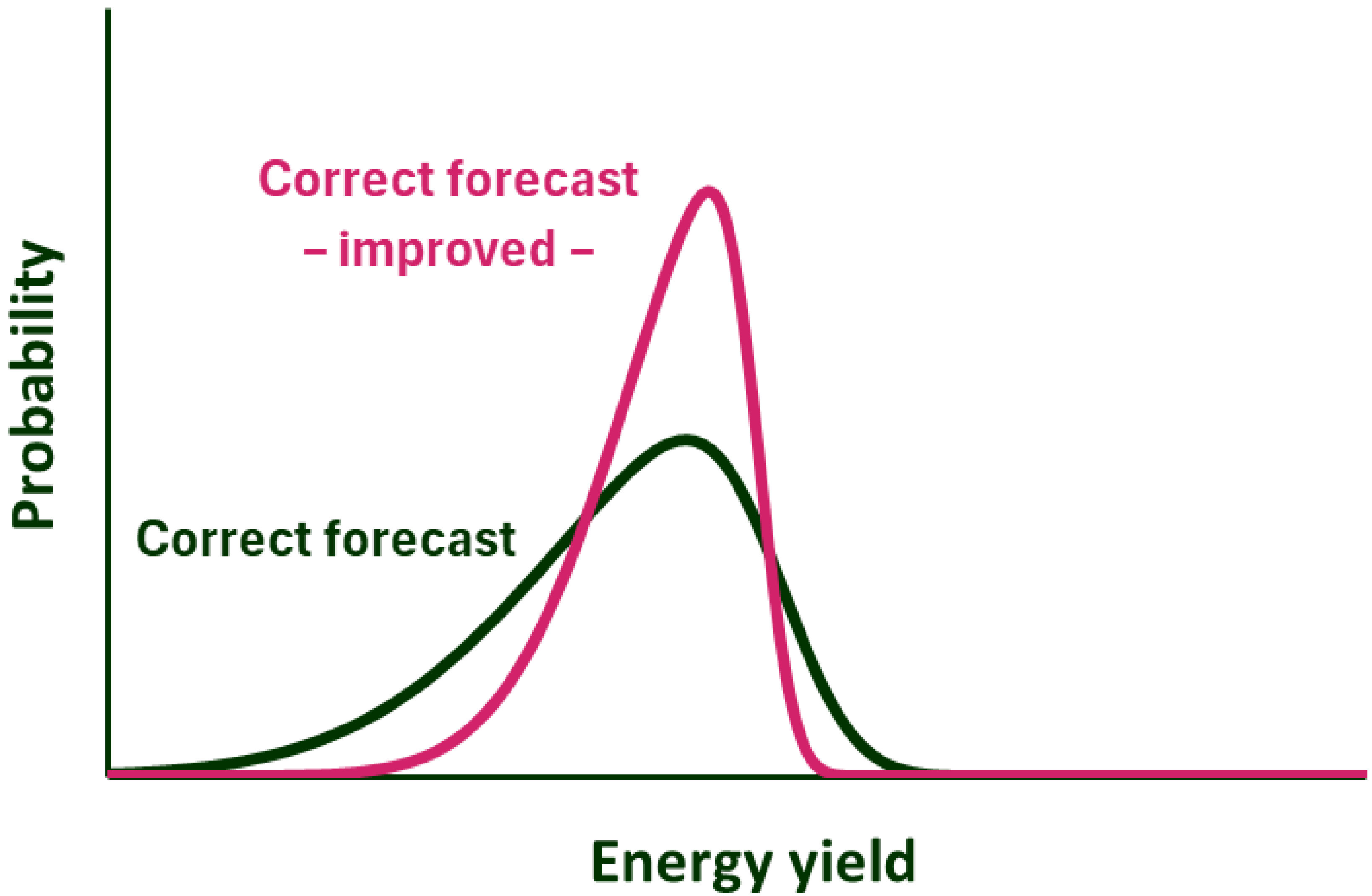
Research opportunities — more ideas

SunSolve

- Comparisons to experiment
- Expand models
  - Thermal
  - Cell IV(T)
  - Soiling
  - Spectral
  - Sky distribution
  - Availability
  - Degradation
  - Uncertainty
- Tandem behaviour
- Uniformity
- Spatial variation in albedo
- Site dependencies
- Optimise cells/modules for real-world
- New configurations
  - Floating PV
  - Agricultural PV
  - Vertical modules
- Shading, edge brightening and mismatch
- Thermal losses

SunSolve Yield — continual advancement

SunSolve



Thank you