Strategies for Rear Irradiance Monitoring in Tracked Bifacial Systems

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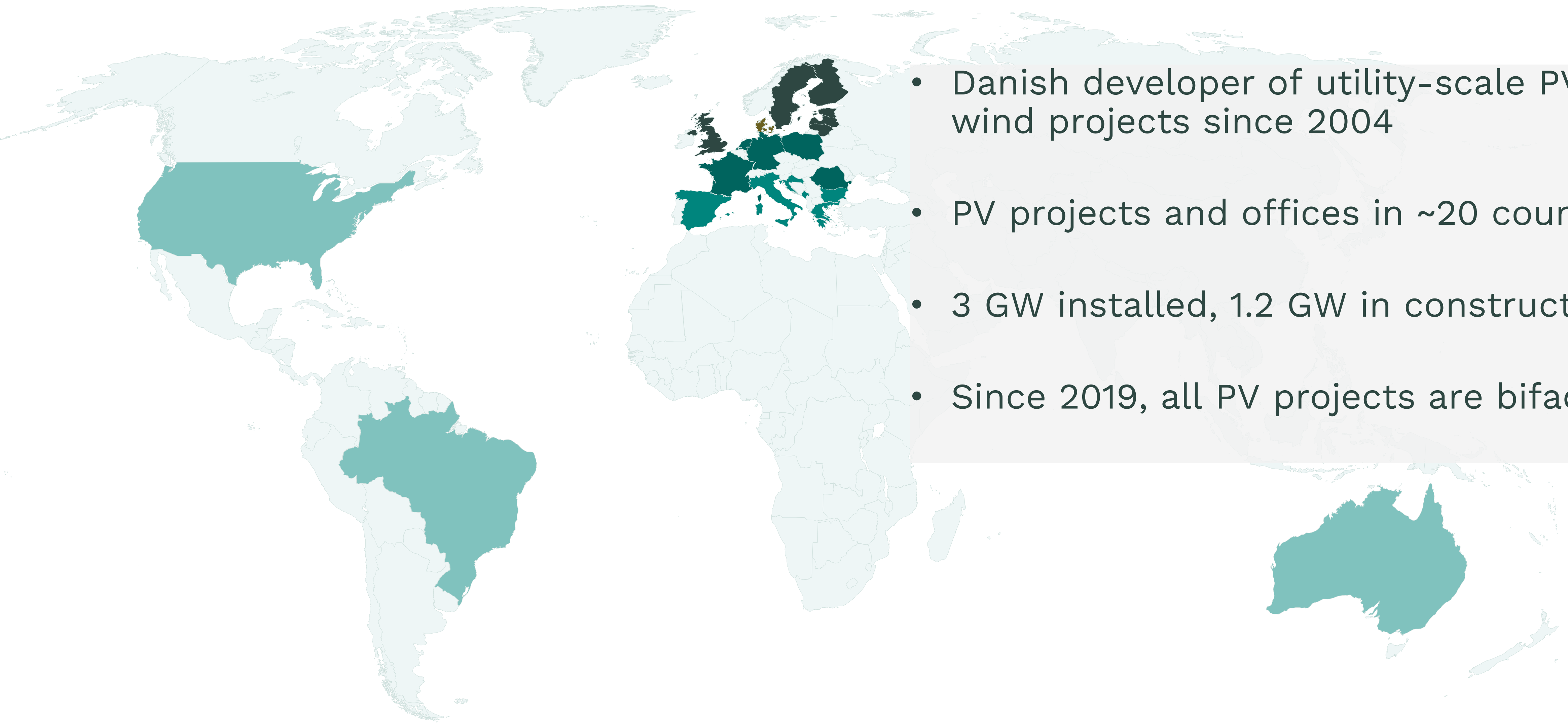
2023 PV Performance Modeling Workshop
Salt Lake City, Utah

European Energy Company Overview



- Danish developer of utility-scale PV and wind projects since 2004
- PV projects and offices in ~20 countries.
- 3 GW installed, 1.2 GW in construction
- Since 2019, all PV projects are bifacial

https://europeanenergy.com/

IEC 61724-1 R_{POA} main guidelines

- **R_{POA} sensors should be mounted at same tilt angle as the modules (directly on module racking), while minimizing module shading.**

IEC 61724-1 (Ed. 2) “Photovoltaic system performance – part 1: Monitoring”

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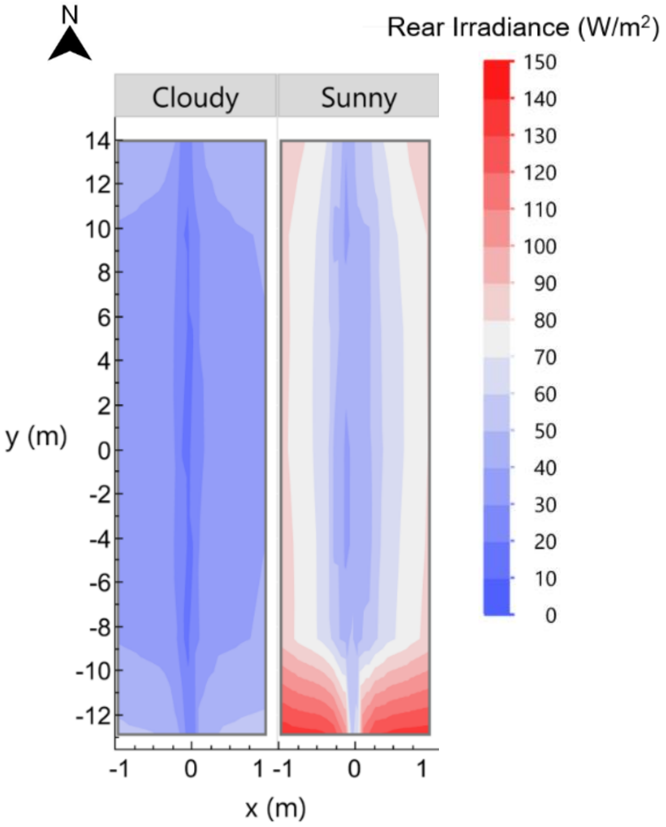

Simulated midday R_{POA} on 1P tracker in Denmark, on cloudy and clear days near summer solstice (height = 1.6 m).

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- **Multiple R_{POA} sensors should be installed to measure the non-uniform illumination throughout the day.**
  - **Provides an 'effective average R_{POA}' for performance equations.**

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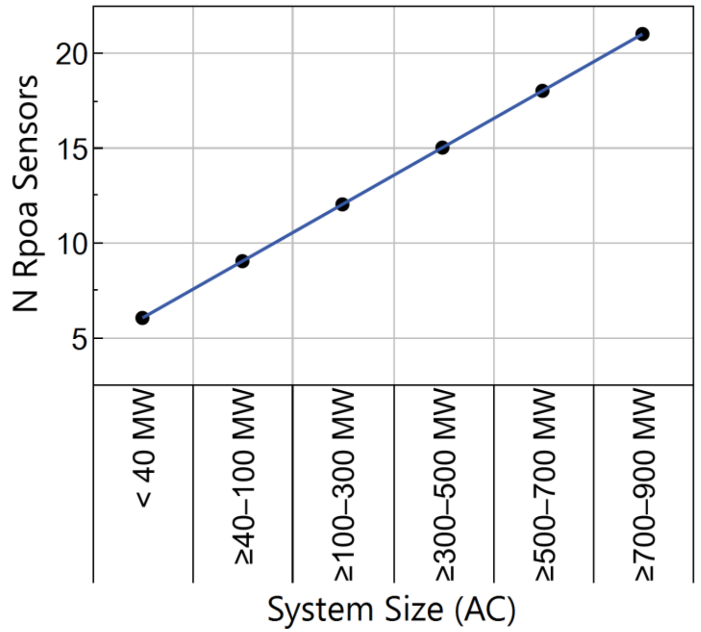
- **For Class A systems, N R_{POA} sensors depends on system size.**
  - **For example, 9 R_{POA} sensors for 50 MWp.**



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Motivation

- **IEC 61724-1 does not give precise recommendations for R_{POA} sensor locations.**
  - **Understandable since R_{POA} non-uniformity depends on structural design, site albedo, solar resource/position.**

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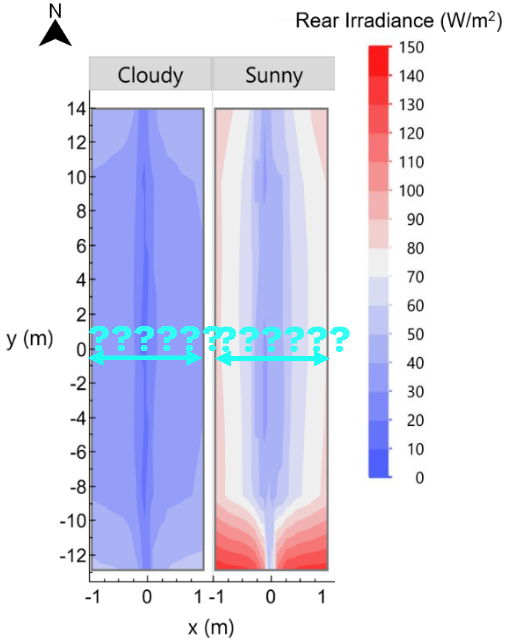
- **Is there a single R_{POA} sensor position that is representative of the long-term average on single-axis trackers (SATs) ?**
  - **We know to avoid sensors on edge modules, but what about E-W positions?**



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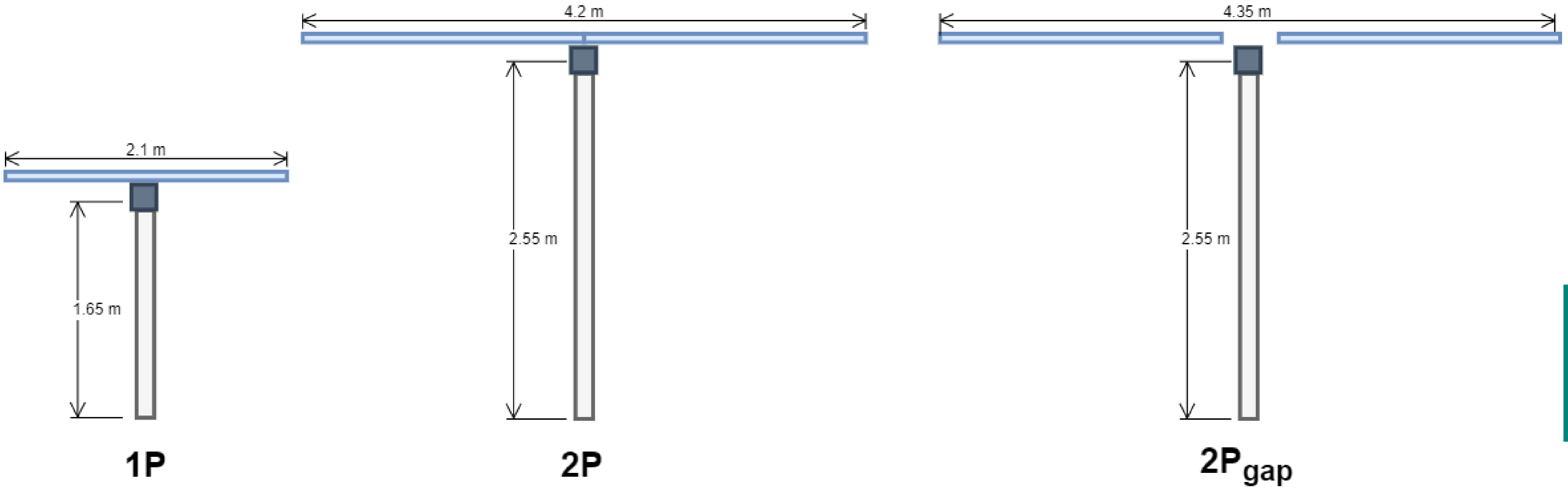
- **IEA PVPS 13 subtask 2.3 working on *<u>Bifacial Tracking Systems</u>* report (Q4-2024).**
    - **Subsection on *Instrumentation best practices for performance monitoring***

Methods

- Ray trace simulations of 3 common SAT designs using *bifacial_radiance*.[1]
  - 1 module in portrait (1P),
  - 2 modules in portrait (2P)
  - 2P with gap ($2P_{Gap}$)



*all three systems have 80 cm clearance when surface_tilt=±60°

[1] Deline, C. & Ovaitt, S. https://github.com/NREL/bifacial_radiance

Methods

- **Annual simulations of 3 systems at 795 locations using the Cumulative Sky method.[1]**
  - Hourly meteo data retrieved from EnergyPlus Weather (EPW) database.[2]
  - Diurnal broadband albedo (ρ) data derived from MODIS MCD43GF black sky (BSA) and white sky (WSA) spectral albedo.[3,4]

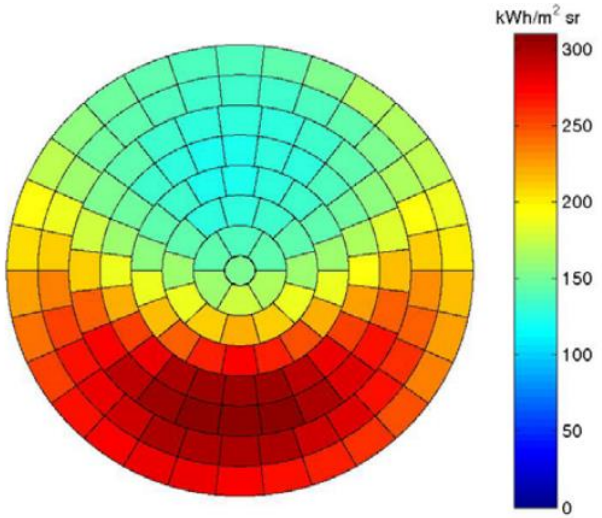


Figure 1 Cumulative diffuse sky radiance distribution for Oslo (based on 10yr mean solar data).

(Robinson and Stone, 2004)

[1] Robinson, D., & Stone, A. (2004). Irradiation modelling made simple
[2] https://climate.onebuilding.org/
[3] https://lpdaac.usgs.gov/products/mcd43gfv006/
[4] Blanc, P. et al., (2014). Twelve monthly maps of ground Albedo parameters derived from MODIS data sets.

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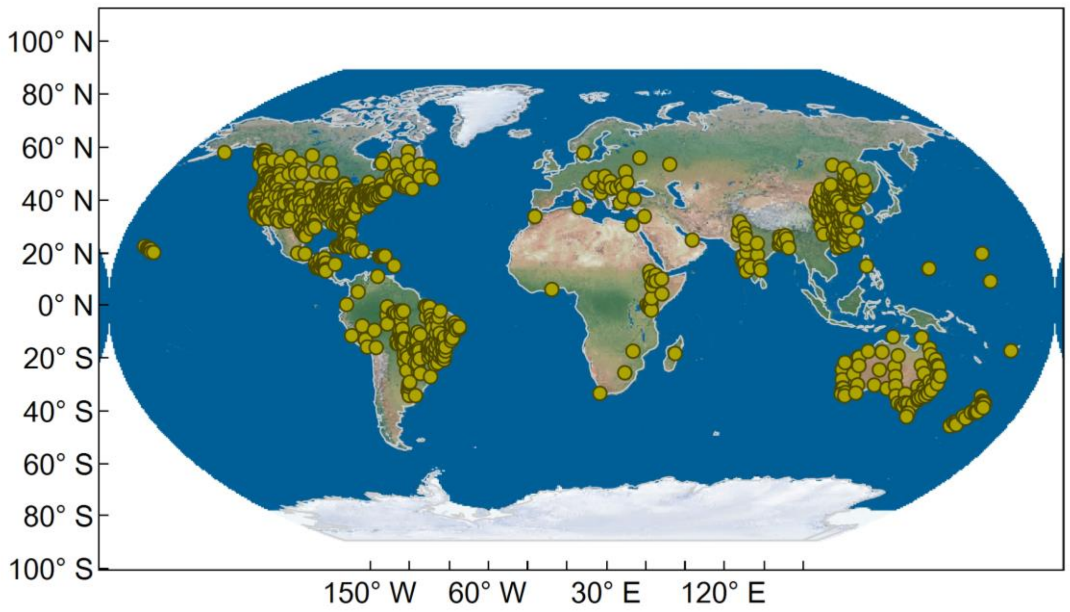

Map of locations studied

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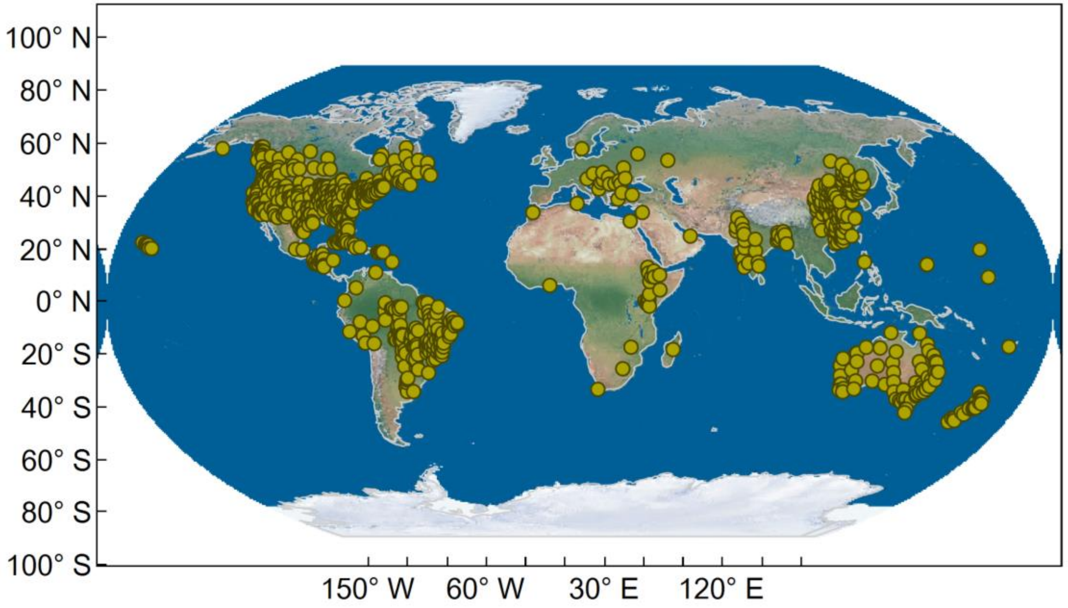

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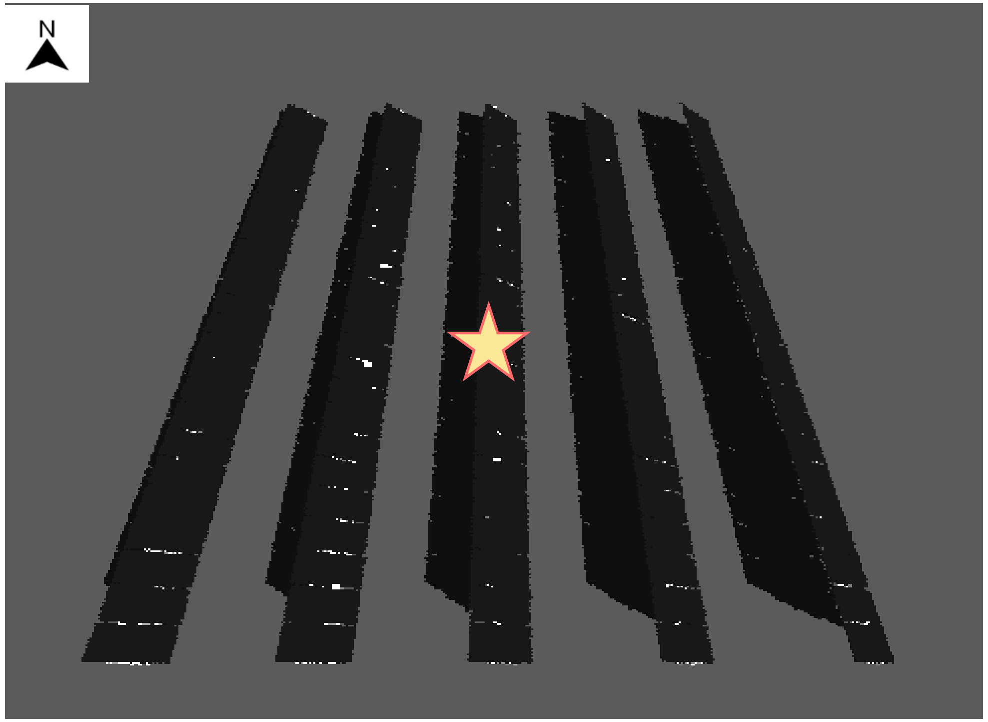
Simulation Details

- We only considered the ***center*** module of the ***middle*** tracker in a 5 row system.
  - GCR = 0.43 (flat terrain)
  - Large area PV modules (2.1 x 1.3 m),
  - square torque tube (15 x 15 cm) with 11 cm distance to PV module (z-gap)
  - Standard backtracking with ±60° limit



Aerial view of 1P scene

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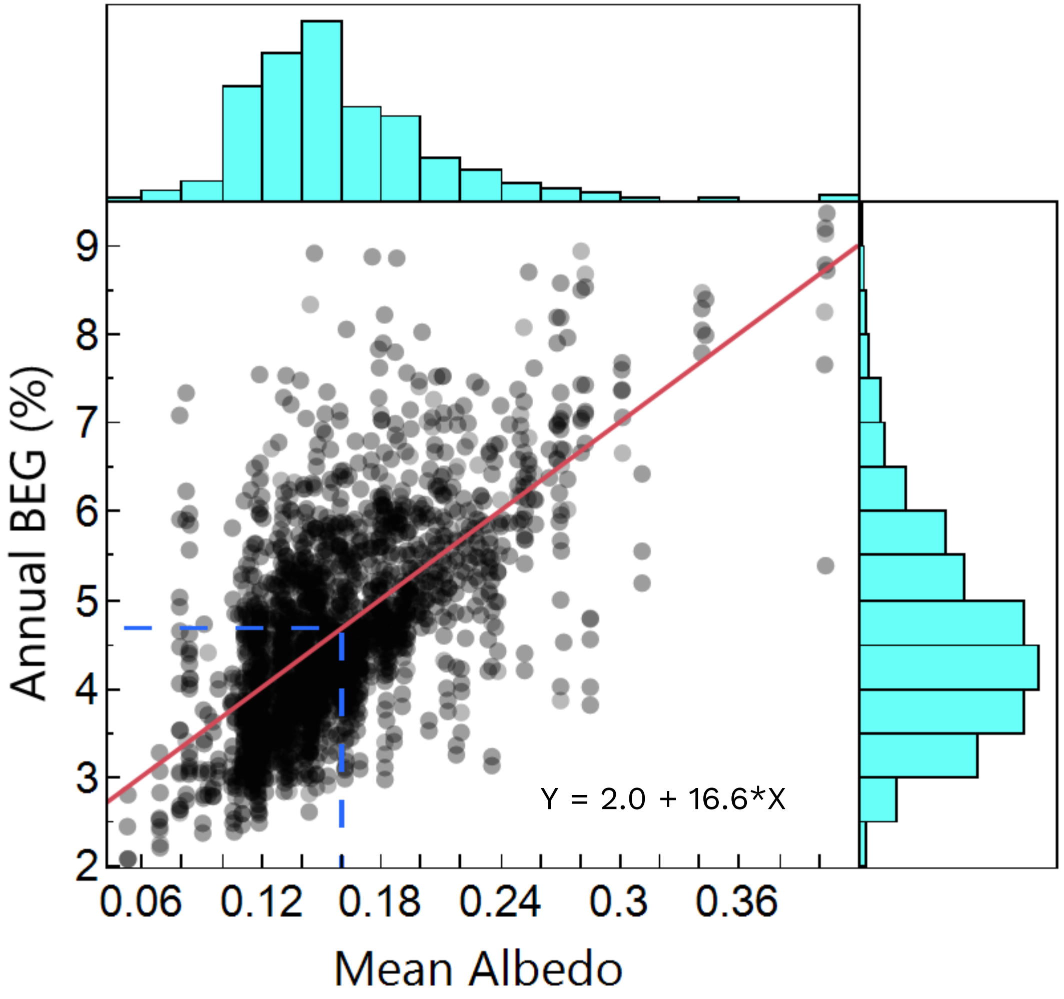
Results: Bifacial Energy Gain

- Mean albedo of 795 locations = 0.16 ±0.05 (1σ)

System	Mean BEG (%)	Std Dev (%)
1P	4.42	1.09
2P	4.26	1.05
2P_Gap	5.59	1.54

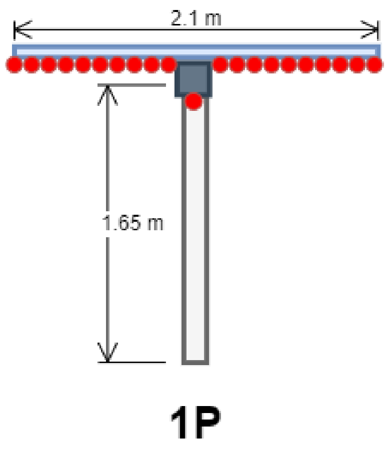
$$BEG = \frac{BF \cdot R_{POA}}{G_{POA}} * 100$$

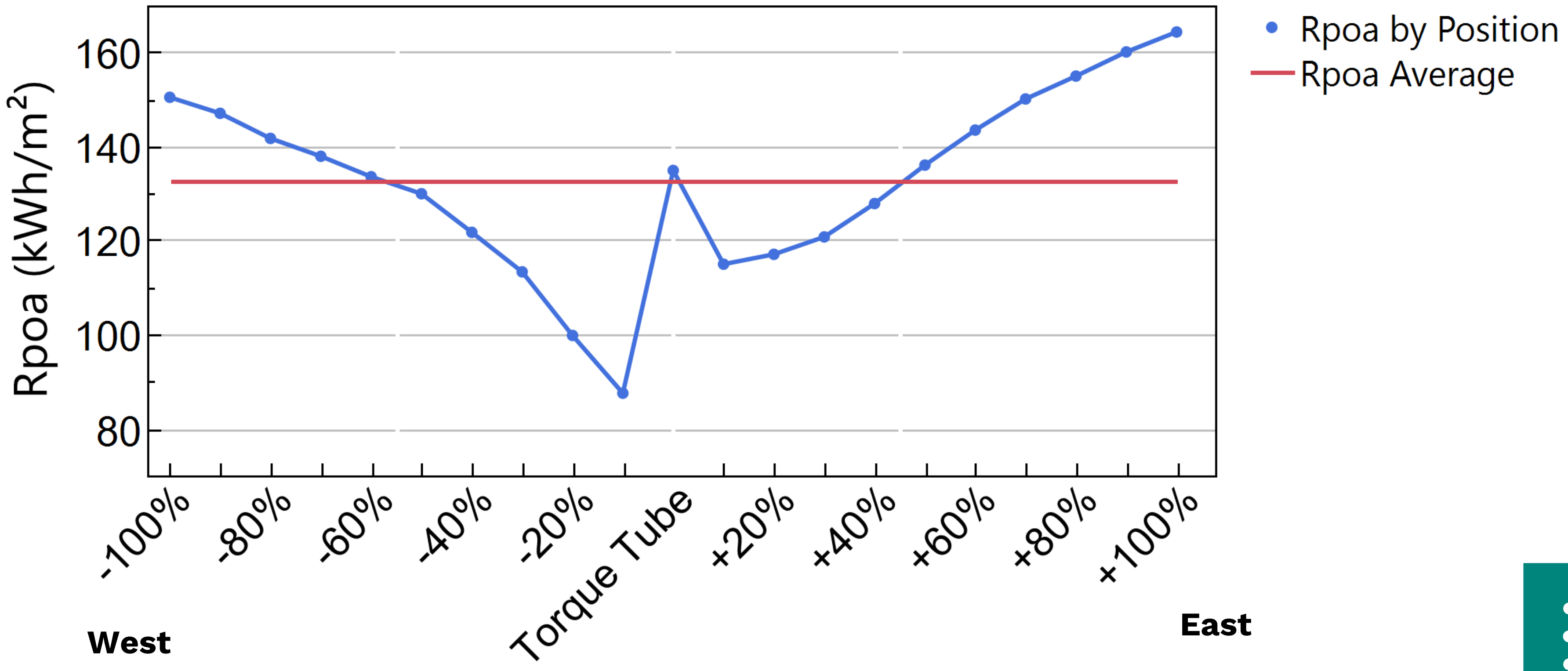
$$BF = 0.7$$



*Average albedo may be lower than the 0.2 assumption because many EPW stations are near urban centers.

Example Results: 1P system in SLC, Utah (40.77º N, 111.97º W)





- R_{POA} sensors considered at 20 equidistant locations on the backside POA, plus one sensor on the torque tube.
- Torque tube sensor is displaced by 26 cm from the backside POA.

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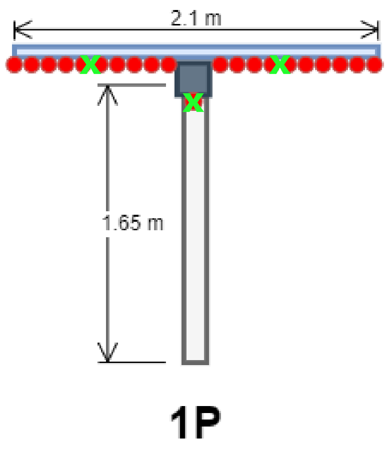

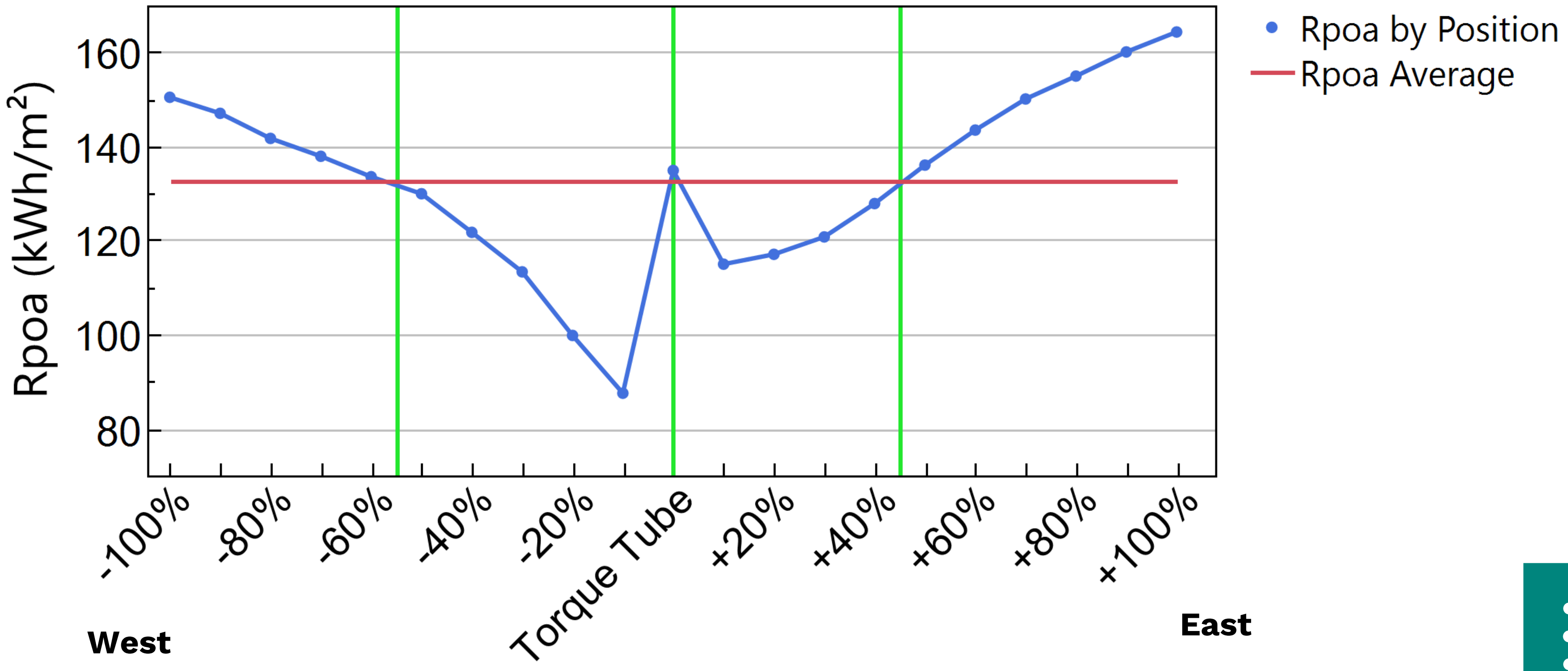

- At this location, sensors at/near -55% and +45% from the torque tube give best match to the long-term R_{POA} average.
- Notably, a sensor on the torque tube is within 2% of the R_{POA} average.

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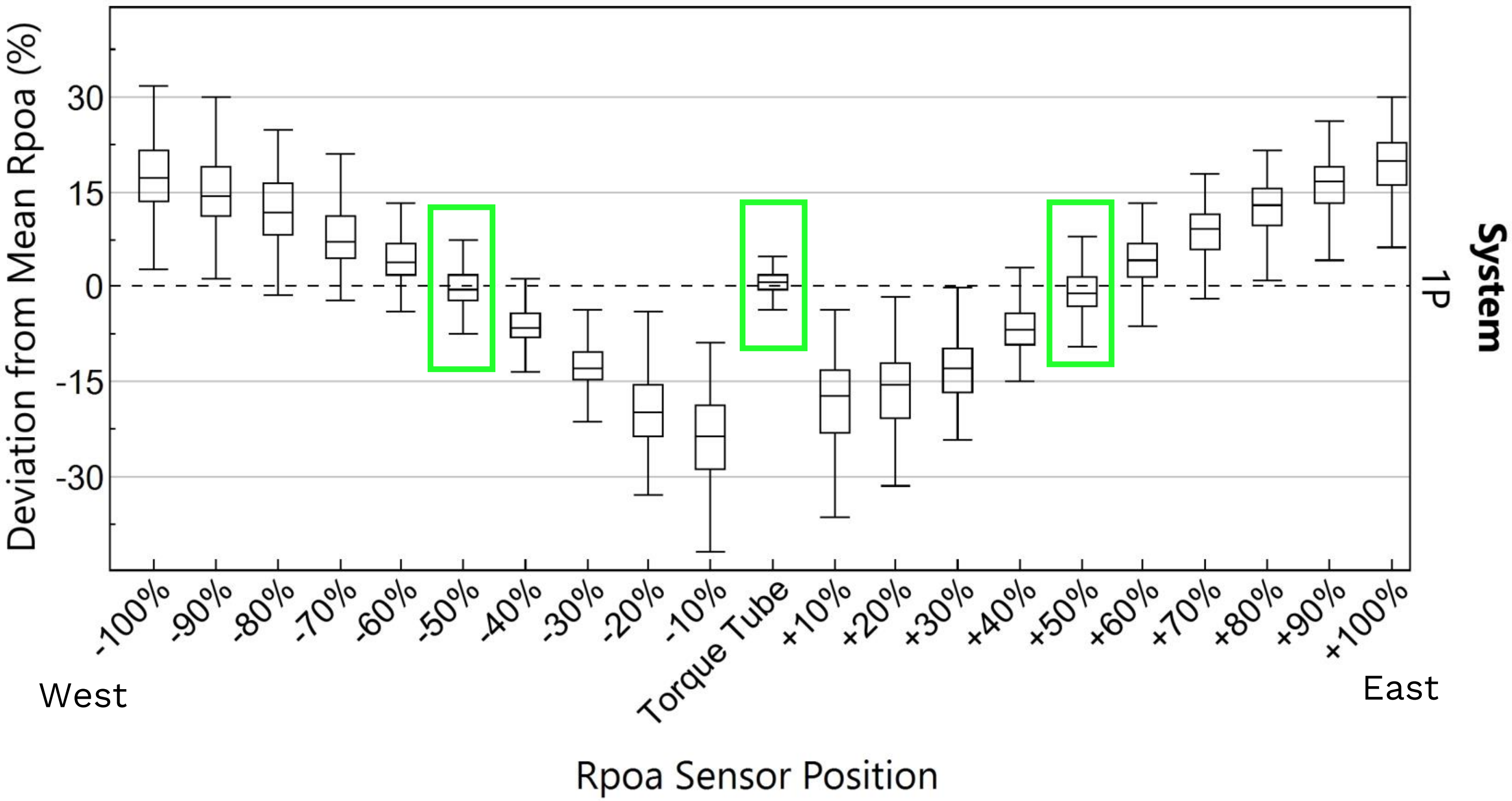
Results from 1P system simulated at 795 locations

- On torque tube and ±50% from torque tube agree best to average.
- These points are w/in 3% of mean R_{POA} for 50% of sites studied.



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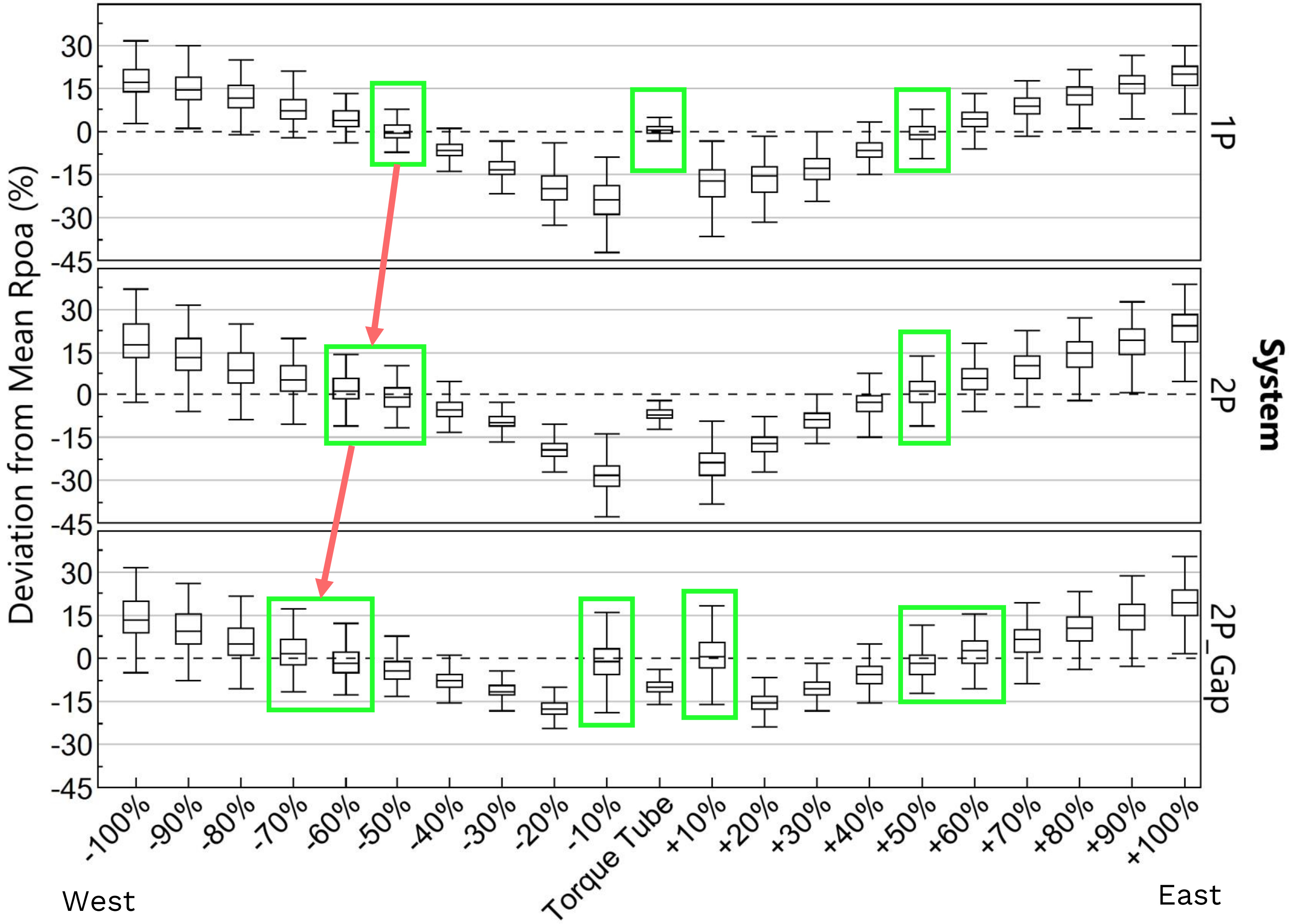
Results from 1P, 2P and $2P_{Gap}$ systems at 795 locations

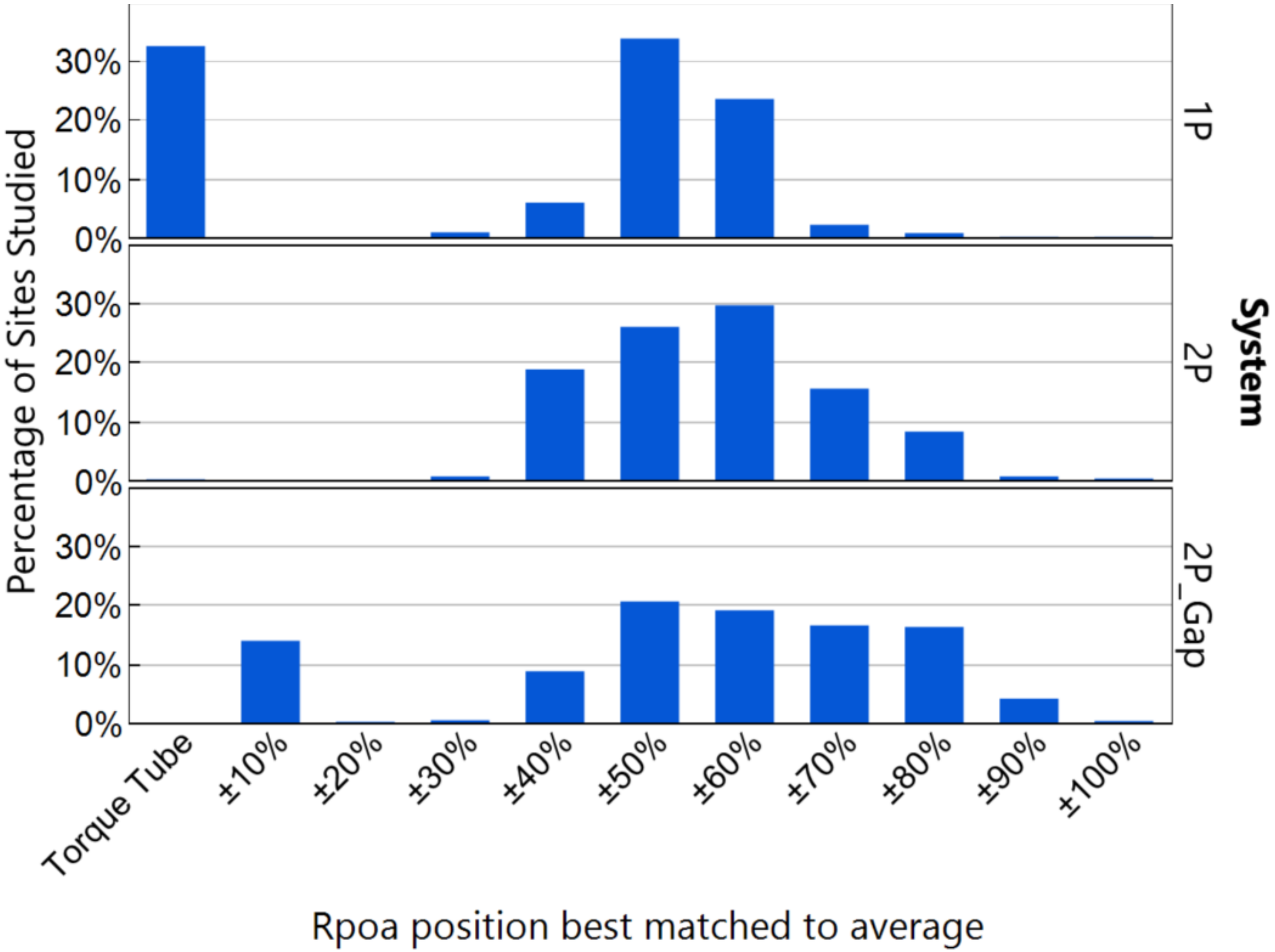
- 2P has nearly the same results as 1P:
  - ±50% / ±60%
- $2P_{Gap}$ is unique, with narrower and wider R_{POA} positions than 1P/2P:
  - ±10% from tube
  - 50%–70% from tube



Distribution of single R_{POA} sensor positions that best represent average R_{POA}

- 795 locations shown here.

- Causal analysis for why results are sometimes different across locations, still not clear.
  - We've checked correlations with: Albedo, latitude (average AOI), and solar resource.

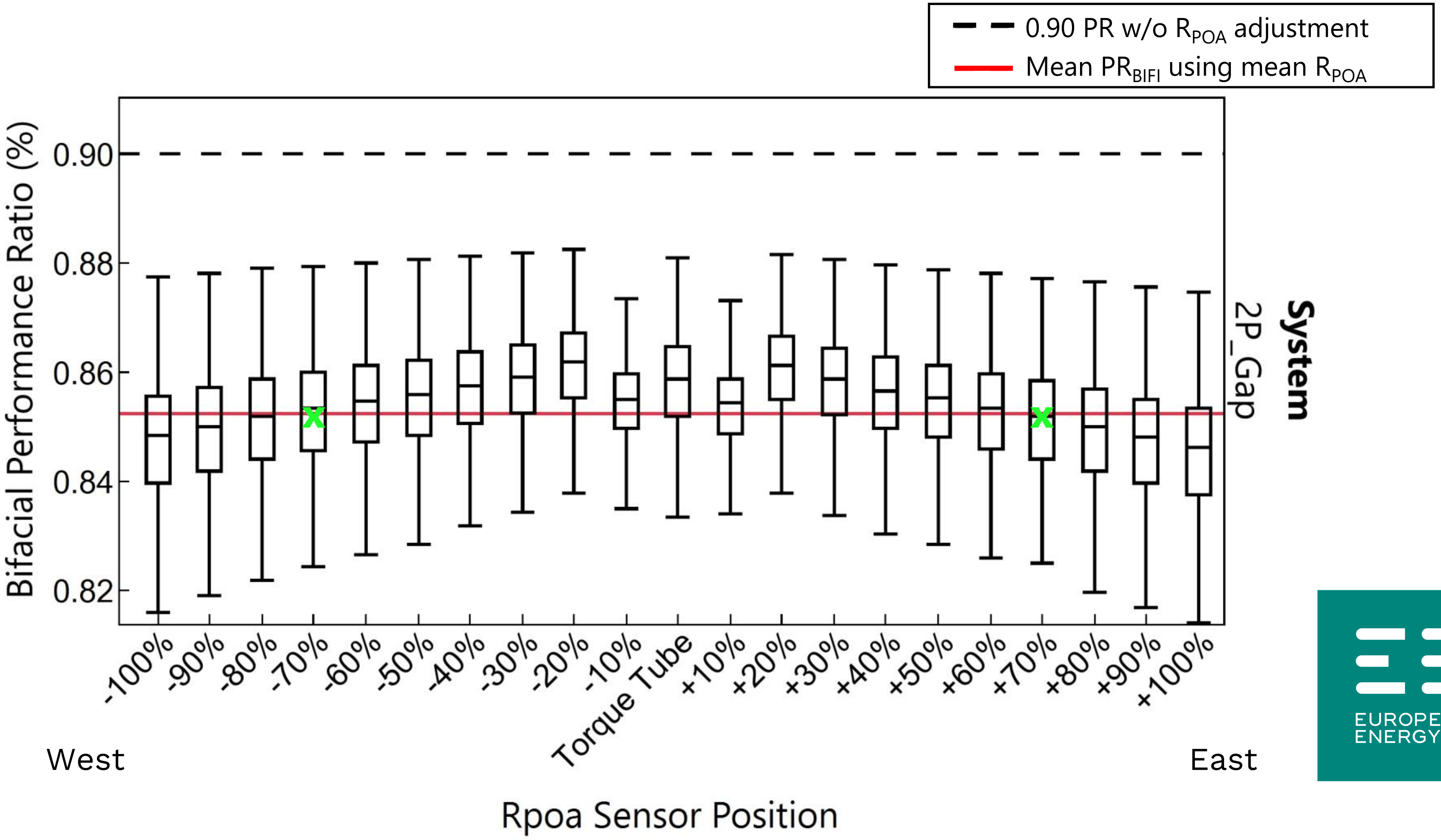


Effect of R_{POA} sensor placement on bifacial performance ratios ($2P_{Gap}$ example)

$$PR_{Bifacial} = \frac{Y_f}{Y_r \cdot BIF}$$

$$BIF = \left(1 + BF \cdot \frac{R_{POA}}{G_{POA}}\right)$$

- Using R_{POA} at ~70% from torque tube gives best match to average.



Validation with $2P_{Gap}$ system at DTU Risø (55.7ºN, 12.1ºE)

- 2 Mini modules with ten isolated cSi cells used to study nonuniformity on $2P_{Gap}$.[1]
- 8 months of electrical, G_{POA} and R_{POA} data used to calculate PR_{BIFI}.

Backside of a $2P_{Gap}$ system. The black mini modules contain 10 cSi cells to measure R_{POA} nonuniformity

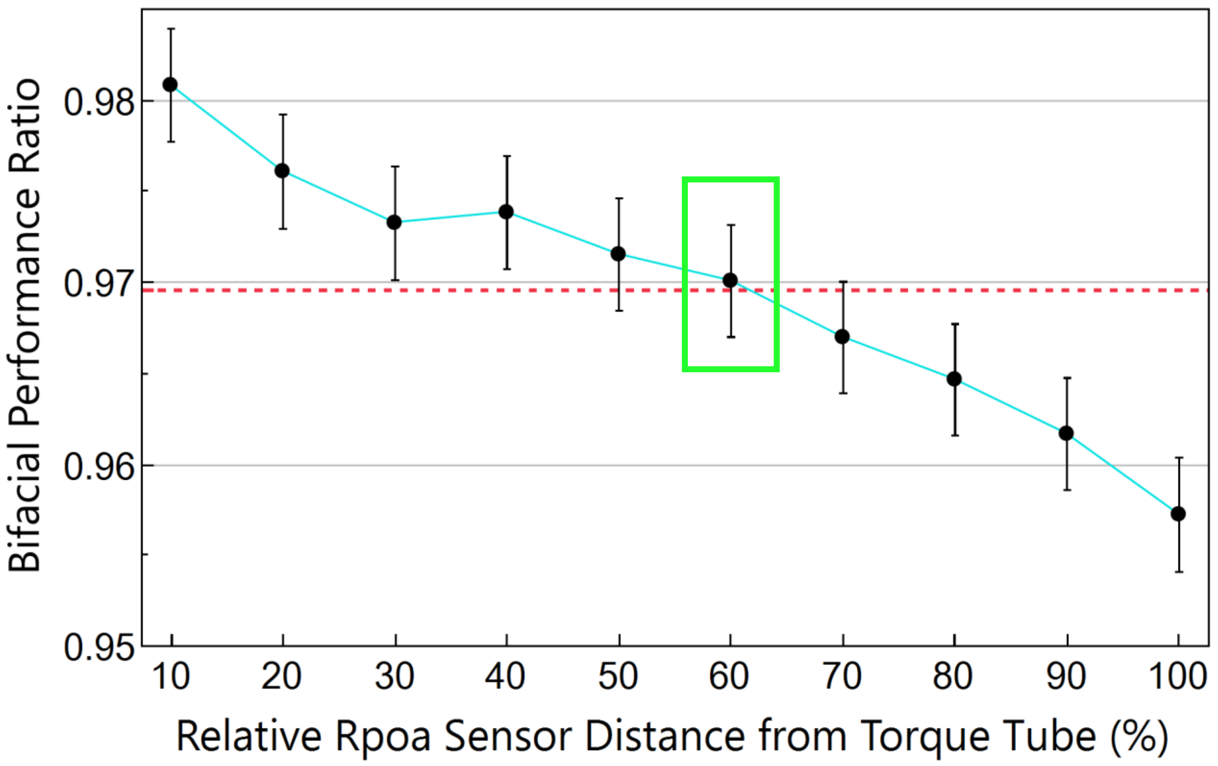
[1] Riedel-Lyngskær, N., et al., (2020). *47th IEEE PVSC (*10.1109/PVSC45281.2020.9300608*)*

Validation with $2P_{Gap}$ system at DTU Risø (55.7°N, 12.1°E)

- High-res R_{POA} measurements show **60% from torque tube** gives best match to average PR_{BIFI}.

$$PR_{Bifacial} = \frac{Y_f}{Y_r \cdot BIF}$$

$$BIF = \left(1 + BF \cdot \frac{\boldsymbol{R_{POA}}}{G_{POA}}\right)$$



PR_{BIFI} calculated over 8 months using R_{POA} from ten cSi cell locations and DC P_{MAX} data from 6.5 kWp string. Error bars show 95% CI of mean using hourly PR_{BIFI}.

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Conclusions

When assessing bifacial performance on *annual* time scales...

- 1P systems are the only structure where R_{POA} sensor placement on the torque tube appears to be a good idea.
- For 1P and 2P, R_{POA} sensors at ±50% from torque tube are within 5% of the average R_{POA}, at 70% of the locations studied.
  - For $2P_{Gap}$ systems, a wider sensor placement (60%–70%) is required for < 5% error.
- Bifacial PR can be biased by ~2.5% if an R_{POA} sensor is placed *anywhere* on SAT.
  - This can be reduced if positions specific to 1P, 2P and $2P_{Gap}$ systems are selected.

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Thank You!

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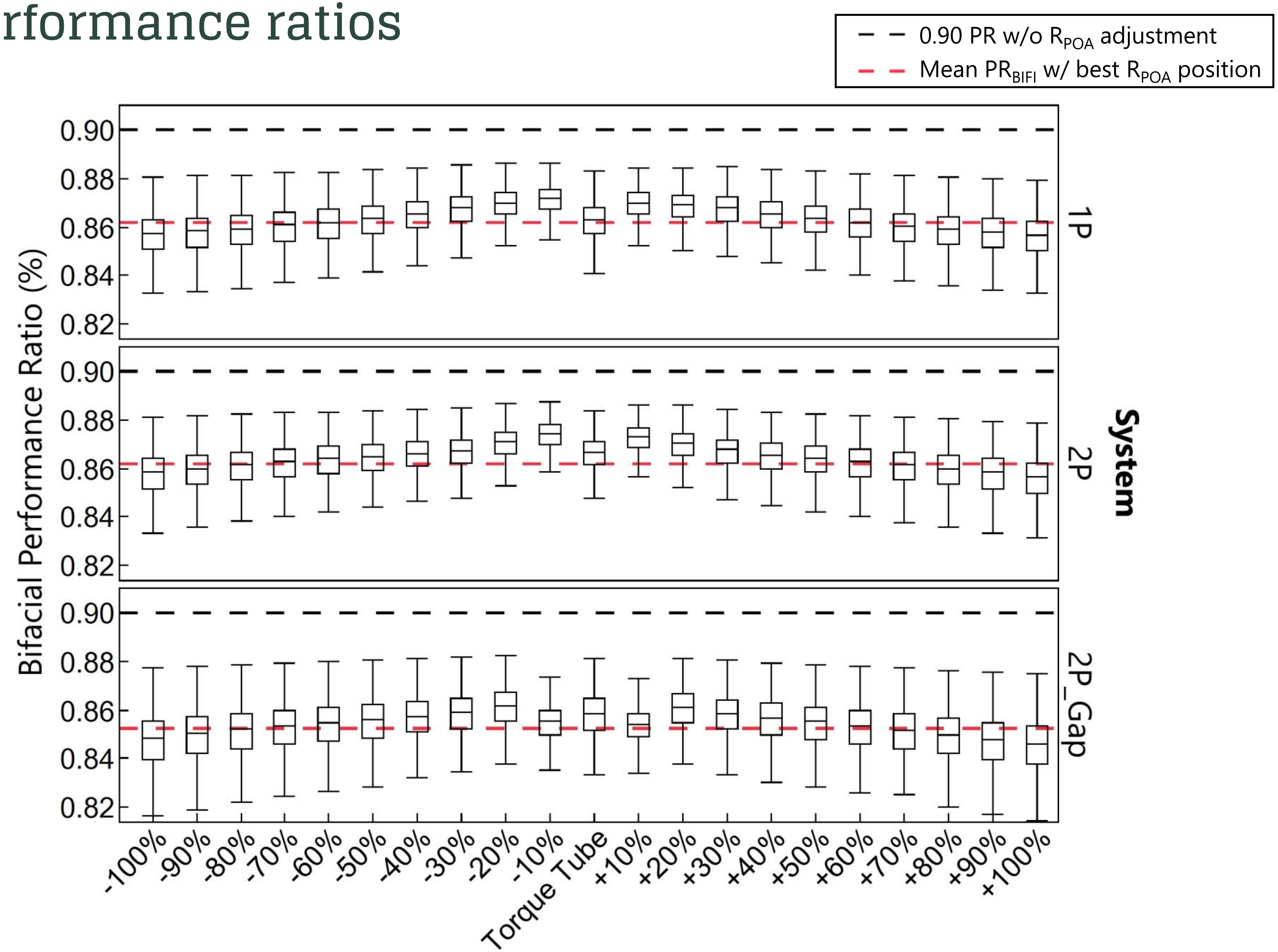
APPENDIX SLIDES

Effect of R_{POA} sensor placement on bifacial performance ratios

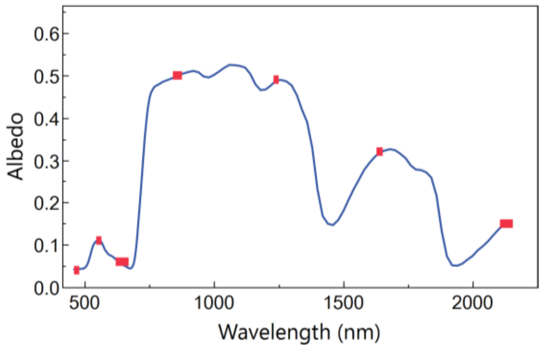


Broadband Albedo from MODIS spectral albedo

- For each location, collect monthly black sky and white sky spectral albedo from MODIS MCD43GF
  - Use data reported at the middle of the month

- Average the 7 spectral BSA and WSA bands to get average BSA and WSA.

- Using DNI and GHI data from the EPW file, calculate albedo (ρ):
  - $\rho = WSA + \frac{DNI \cdot \cos(SZA)}{GHI} \cdot (BSA - WSA)$



Example spectral albedo curve sampled at 7 MODIS wavelength channels (red points).

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Blanc, P. et al., 2014. Twelve monthly maps of ground Albedo parameters derived from MODIS data sets. https://doi.org/10.1109/IGARSS.2014.6947177
Lefevre, M. et al., 2013. McClear : a new model estimating downwelling solar. Atmos. Meas. Tech.

Methods

- R_{POA} sensors considered at 20 equidistant locations in POA, plus one on the torque tube.
  - Placed across the middle module within a 22 module string.