

IMPROVING PERFORMANCE RATIO CALCULATIONS BY OPTIMIZING FRONT POA IRRADIANCE SENSOR POSITION

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OTT HydroMet product brands

OUTLINE

☉ Measuring irradiance better

☉ Simulations:

- ☉ Where in the array?
- ☉ Where across the module?

☉ Validation of simulations

☉ Conclusions



SOLAR ENERGY: WHY MEASURE IRRADIANCE BETTER?

☉ **Early development:**

- ☉ Designing appropriate PV system (module type, fixed or tracked, etc.)
- ☉ Identifying optimal site location

☉ **Pre-construction & financial readiness:**

- ☉ Long term energy yield assessment, investment decision

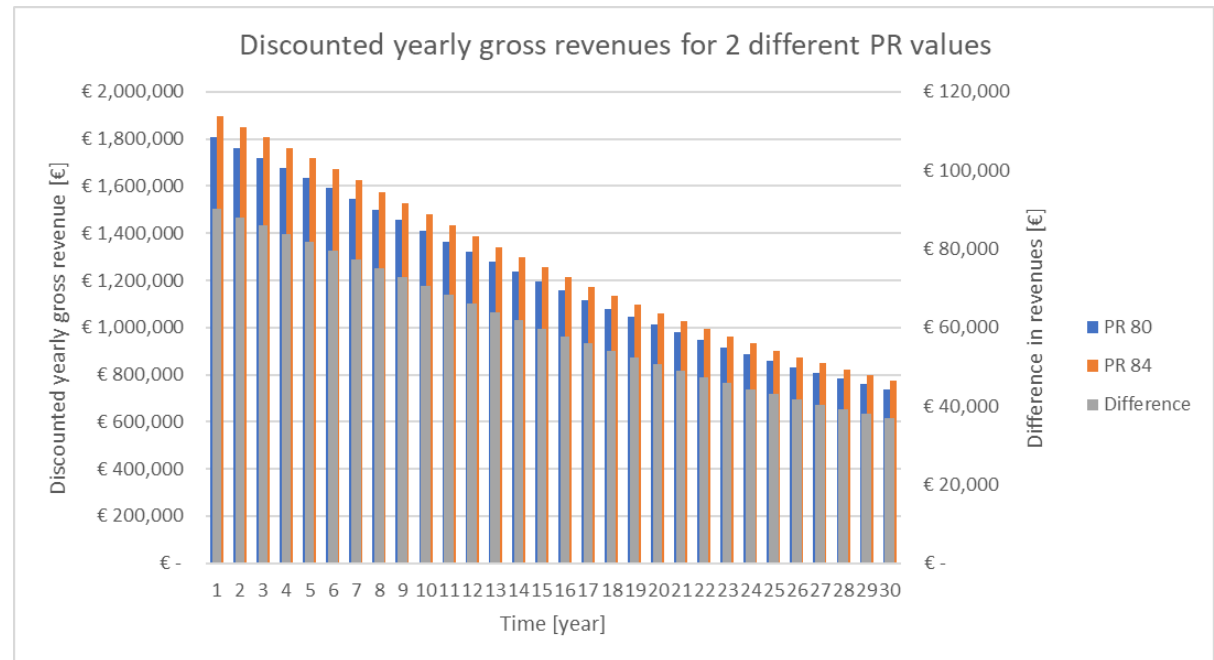
☉ **Operational:**

- ☉ Performance verification
- ☉ Utility production forecasting
- ☉ Portfolio-level site intercomparison
- ☉ Prompt maintenance maximizes production and increases site lifetime

PV PARK VALUATION IMPACT CALCULATION

- 4% irradiance difference → 4% Performance ratio difference
- Gross revenue calculation: $(PSH) \cdot (\text{days}) \cdot (\text{MW}) \cdot (\$/\text{MWh}) \cdot (\text{PR}/100)$
- Example 64 MW PV park in California: $5 \text{ h}^{[1]} \times 365 \text{ d} \times 64 \text{ MW} \times 20 \text{ \$/MWh}^{[2]} \times 0.8$ (yield curve discounting)

- 30-year gross revenues:
 - = \$36M (PR80)
- A 4% decrease in PR:
 - **\$ 1.8 Million** difference present value of PV park



[1] https://emp.lbl.gov/sites/default/files/utility-scale_solar_2022_technical_brief.pdf

[2] Smets A, Jäger K, Isabella O, van Swaaij R, Zeman M. Solar Energy: The physics and engineering of photovoltaic conversion, technologies and systems. Cambridge: UIT Cambridge Limited, 2016. 462 p.

SOLAR ENERGY: HOW TO MEASURE IRRADIANCE BETTER?

☉ Uncertainty:

- ☉ Calibration uncertainty of pyranometers can be $\pm 1\%$
- ☉ Field measurement uncertainty can be $\pm 1.3\text{-}1.7\%$ in economic relevant hours of the day.[1]

☉ Familiar choice: Class A, not Class C

- ☉ RSS uncertainty of ISO9060:2018 requirements:
 - Class C = $\pm 10.3\%$
 - Class B = $\pm 5.6\%$ (4.7% better than C)
 - Class A = $\pm 2.8\%$ (2.8% better than B)
 - Reality: 1.4% (SMP22) to 2.2% (SMP10)

☉ What else?

- ☉ Installation errors (leveling, shading)
- ☉ Dew & frost prevention
- ☉ Sensor siting – In-array and across module

[1] Kipp & Zonen Suncertainty (google app store)

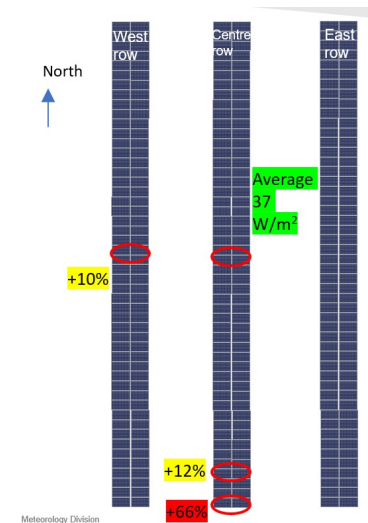
WHERE TO PLACE POA PYRANOMETER?

Previous Work:

- In-plane, rear-side irradiance sensor position for fixed and tracked bifacial modules^{[1],[2],[3],[4],[5]...}

Today

- Frontside irradiance:
 - Where in the park?
 - Where across the module?



[1] "A Spatial Irradiance Map Measured on the Rear Side of a Utility-Scale Horizontal Single Axis Tracker with Validation using Open Source Tools" Riedel-Lyngskæret et al. Proceedings of 2020 IEEE PSC

[2] "Measuring Irradiance for Bifacial PV Systems", Gostein et al. IEEE PVSC, 2021.

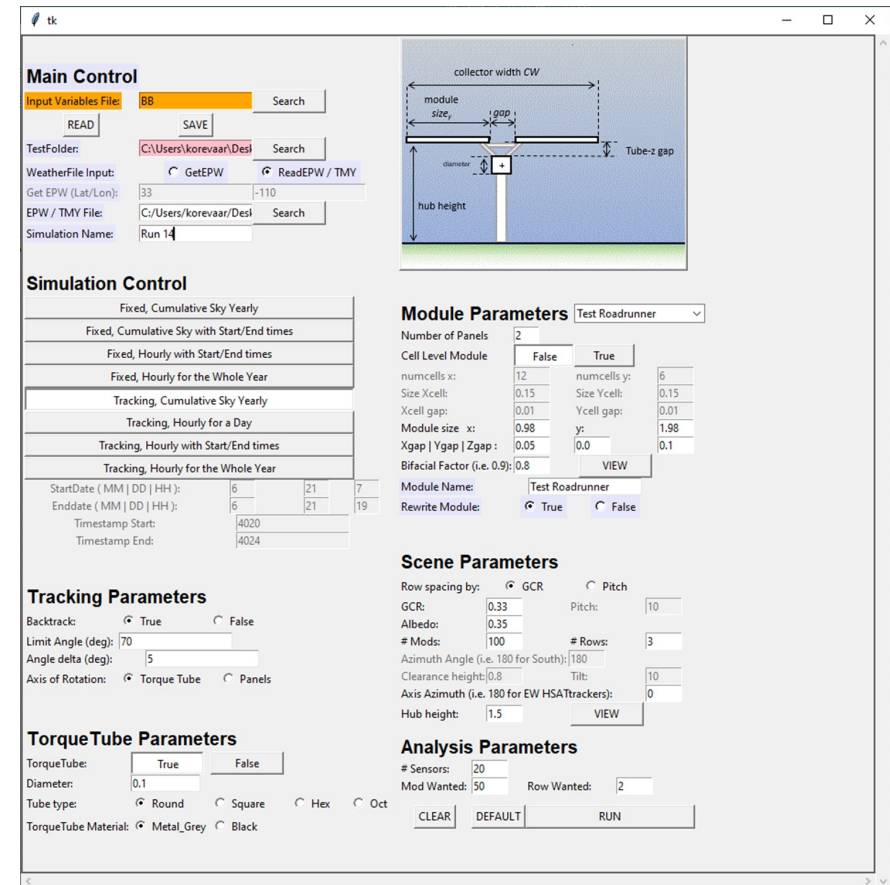
[3] "Simulation and Validation of Bifacial Irradiance Sensor Mounting Position", Korevaar et al. EU PVSEC 2020

[4] "Strategies for Rear Irradiance Monitoring", Riedel et al., PVPMC 2023

[5] "Bifacial photovoltaic Technology: recent advancements, simulation and Performance measurement", M. Aghaei et al., 2022, ISBN:978-1-83968-858-4

NREL BIFACIAL RADIANCE SOFTWARE SIMULATION

- ☼ Software package developed by NREL for bifacial simulations^{1,2} and validated^{3,4}
- ☼ Bifacial Radiance is **python™** based
- ☼ Uses raytracing
- ☼ Solar input:
3 components (GHI, DHI, DNI) and albedo
- ☼ Software GUI →



¹ C. Deline, W. Marion, and S. Ayala, "Bifacial Radiance", Computer Software.

https://github.com/NREL/bifacial_radiance, 2017,

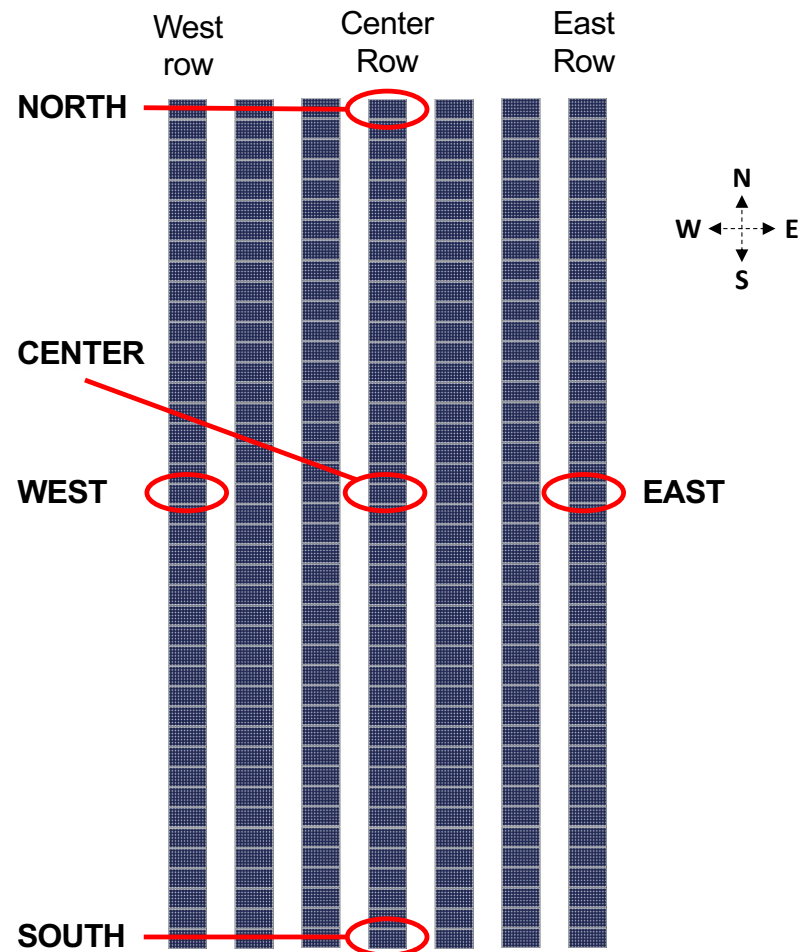
² C. Deline, and S. Ayala, "Bifacial Radiance", USDOE Office of Energy Efficiency and Renewable Energy (EERE), Solar Energy Technologies Office (EE-45), 2017.

³ S. Ayala Pelaez, C. Deline, P. Greenberg, J.S. Stein, and R.K. Kostuk. IEEE J Photovoltaics. 2019.

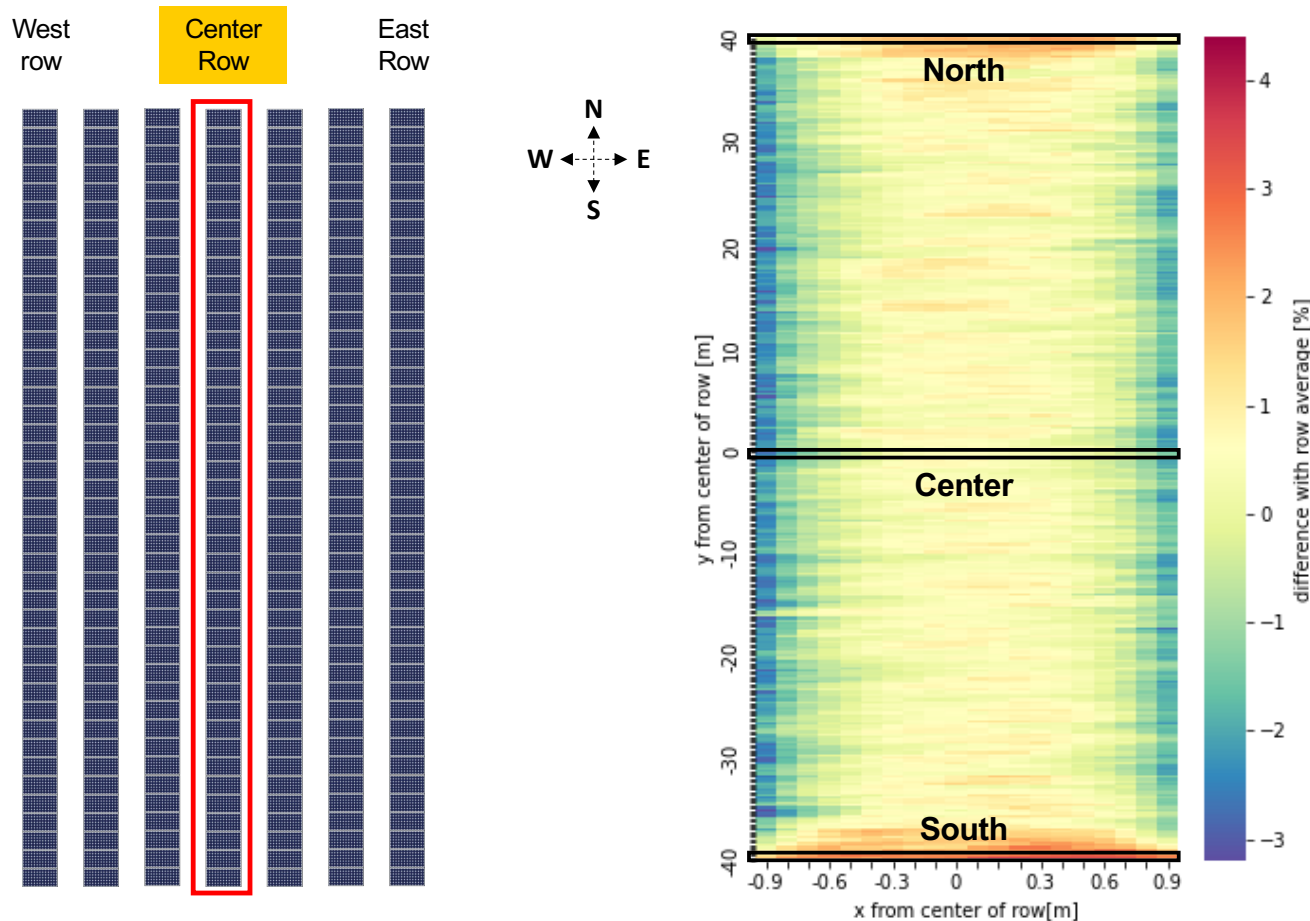
⁴ S. Ayala Pelaez, C. Deline, M. MacAlpine, B. Marion, J. Stein, and K. Kostuk, IEEE J Photovoltaics. 2019

TRACKED PLANT TOP VIEW SIMULATION OF MODULE POSITIONS

Front-side irradiance

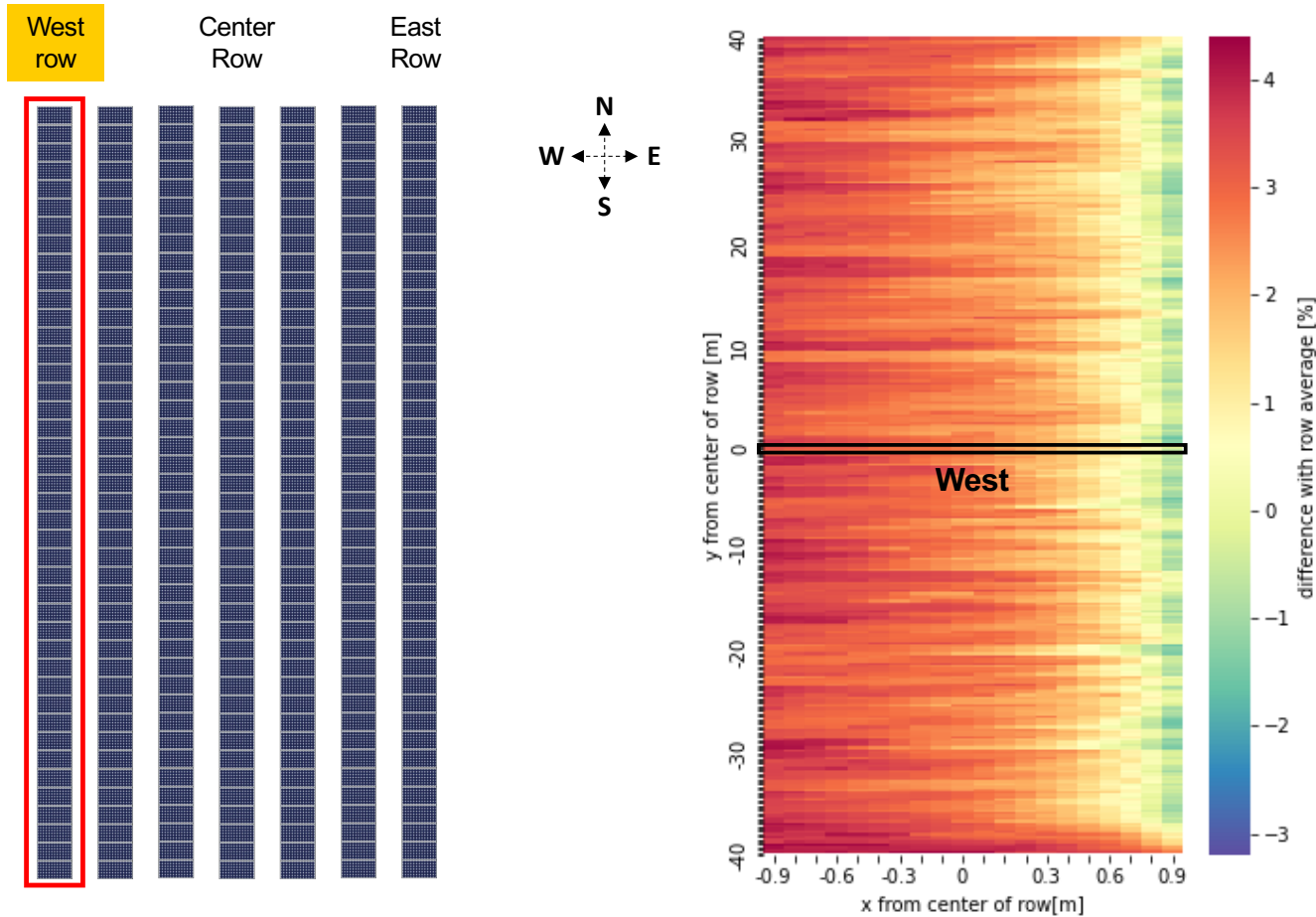


TRACKED PLANT, TOP VIEW, CENTER ROW, YEARLY



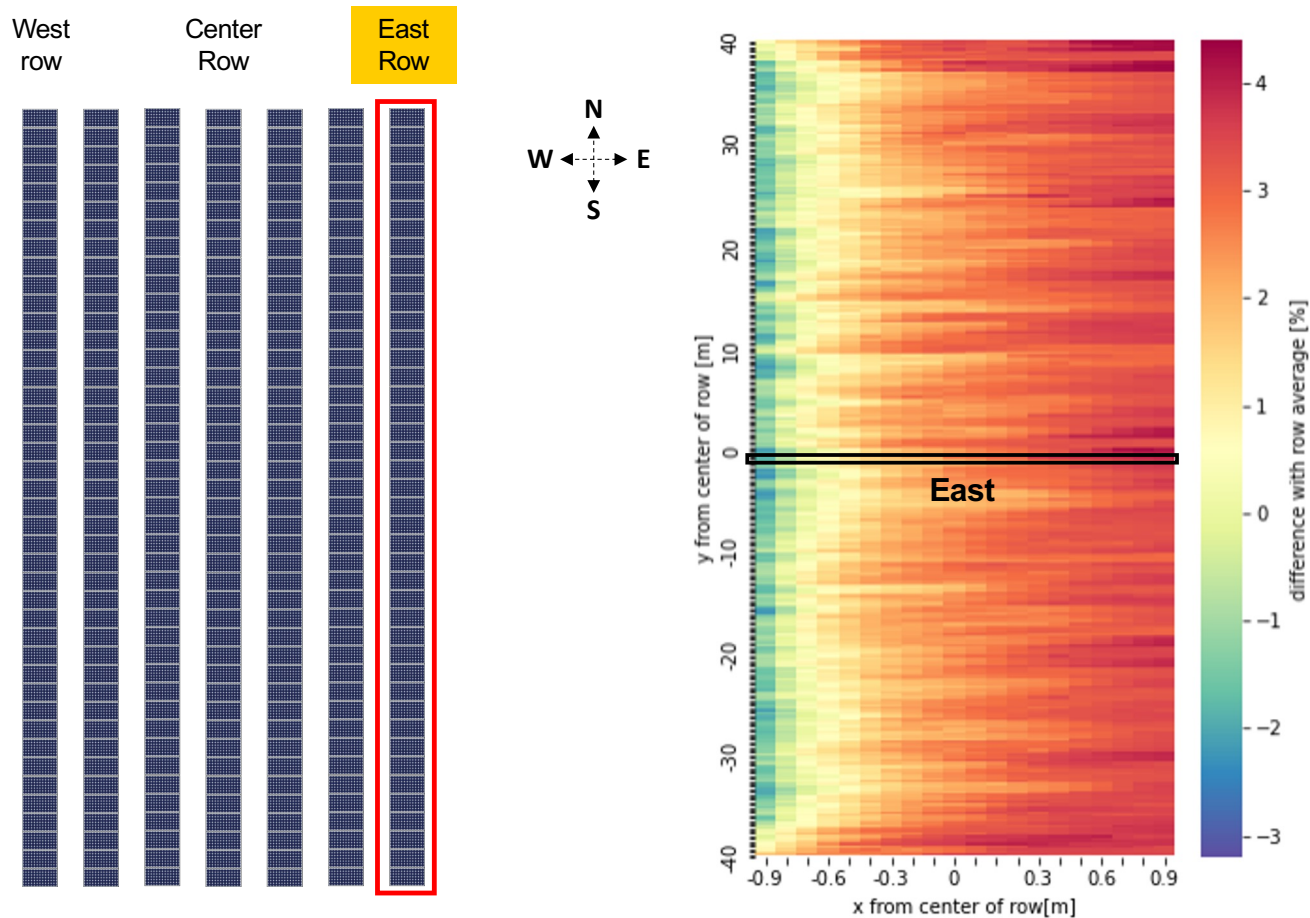
- Center row map of yearly average POA^{front} difference with average of center of plant
- Differences from +4.3 % to -2.3%

TRACKED PLANT TOP VIEW WESTERN ROW



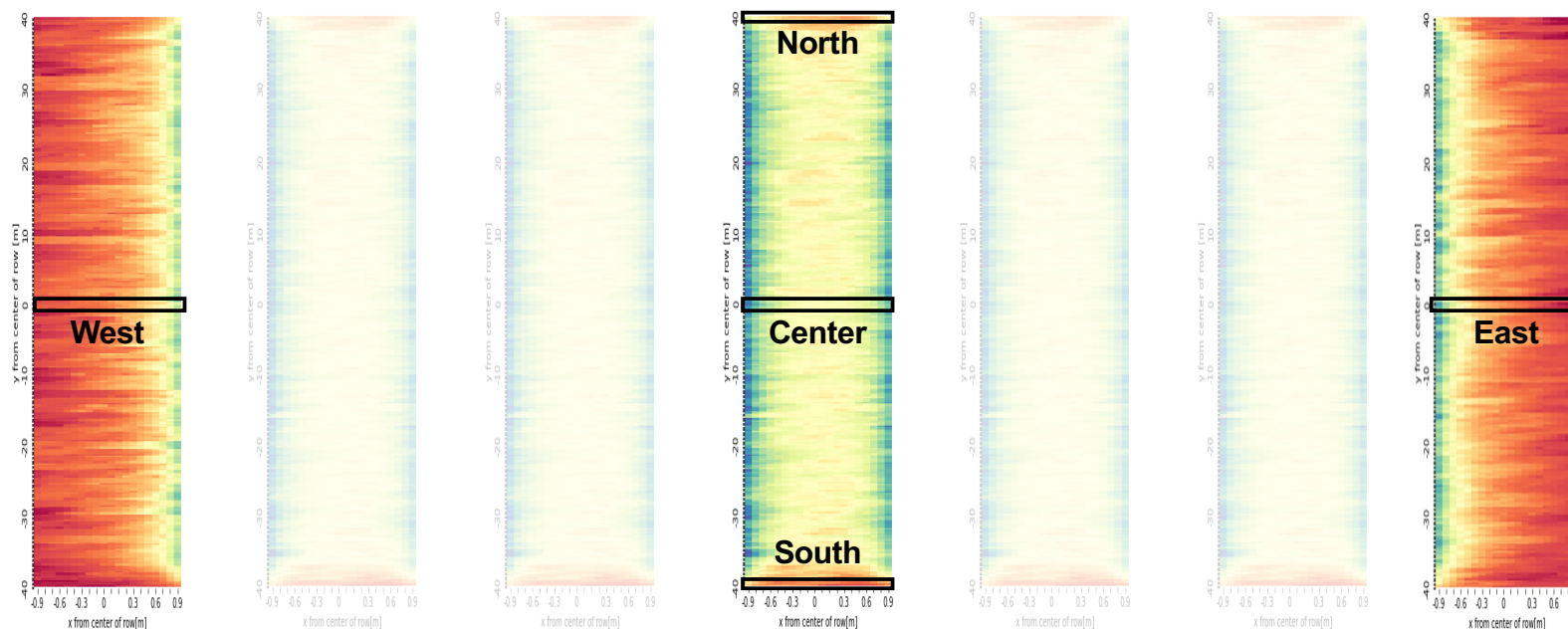
- Western row map of yearly average POA^{front} difference with average center of plant
- Differences from +4.4 % to -1.7%

TRACKED PLANT TOP VIEW EASTERN ROW



- Eastern row map of yearly average POA^{front} difference with average center of plant
- Differences from +4.3 % to -2.3%

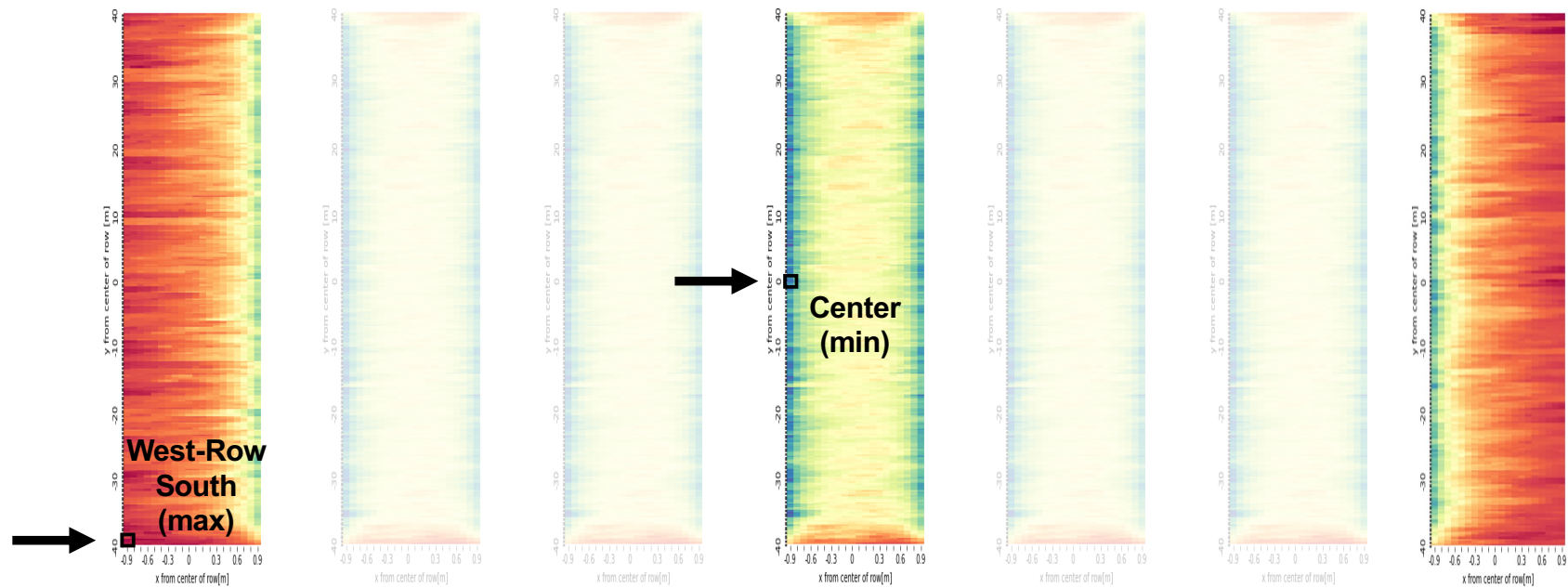
POSITIONAL DIFFERENCE IN MODULE ENERGY OUTPUT



	North	South	West	East
Frontside	+2.0%	+2.2%	+2.3%	+2.1%

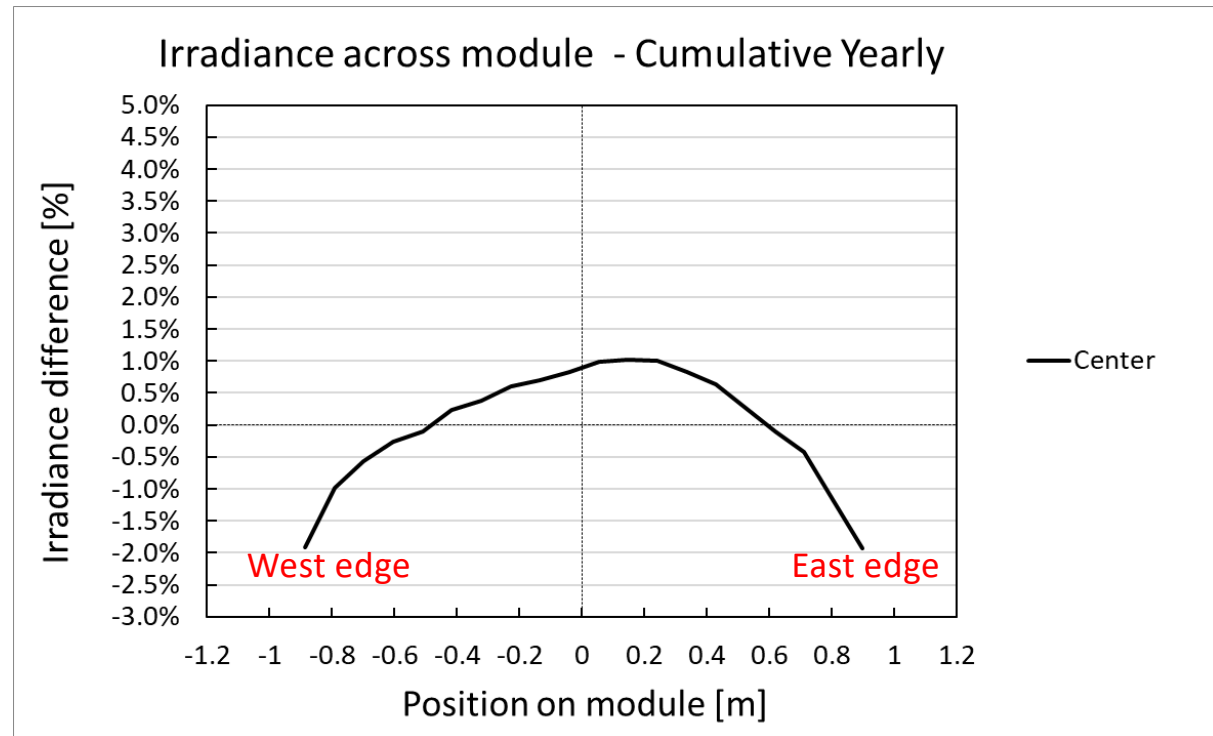
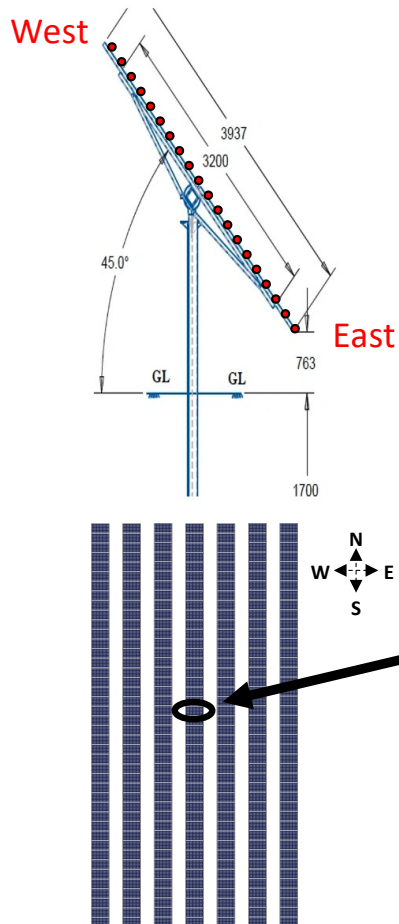
Difference relative to Center Row, Center Module

POSITIONAL DIFFERENCE IN MODULE ENERGY OUTPUT



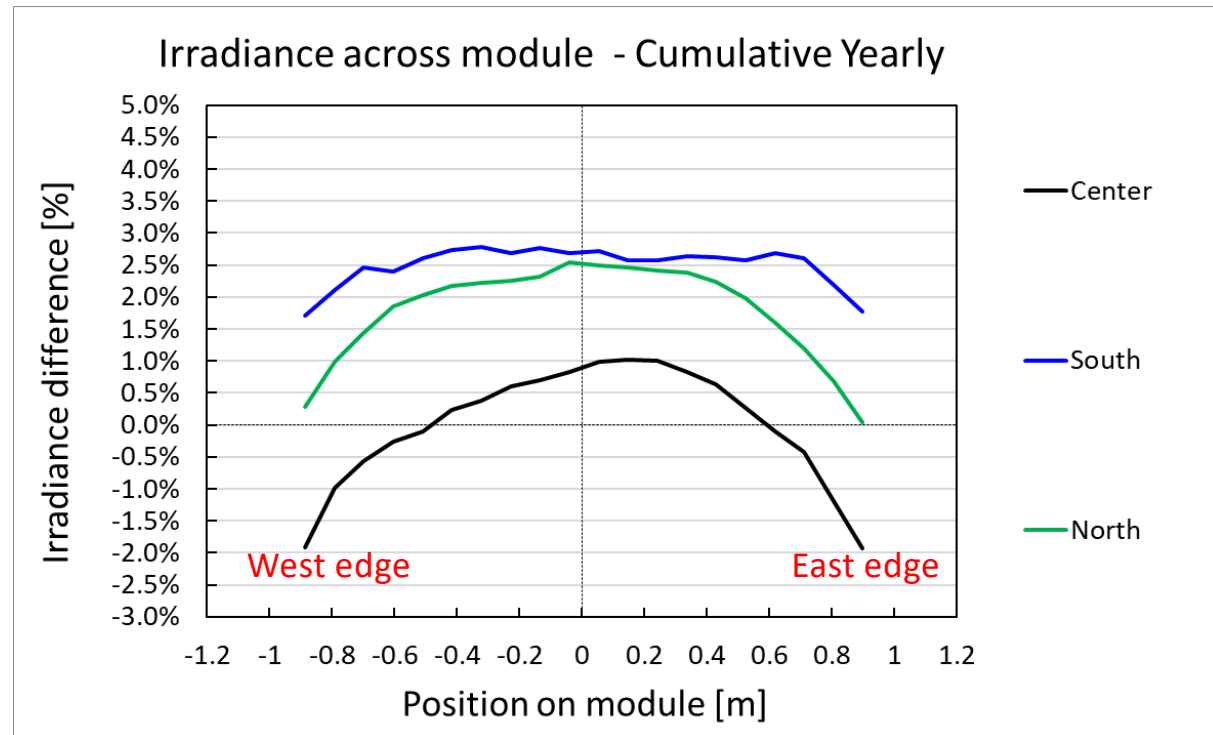
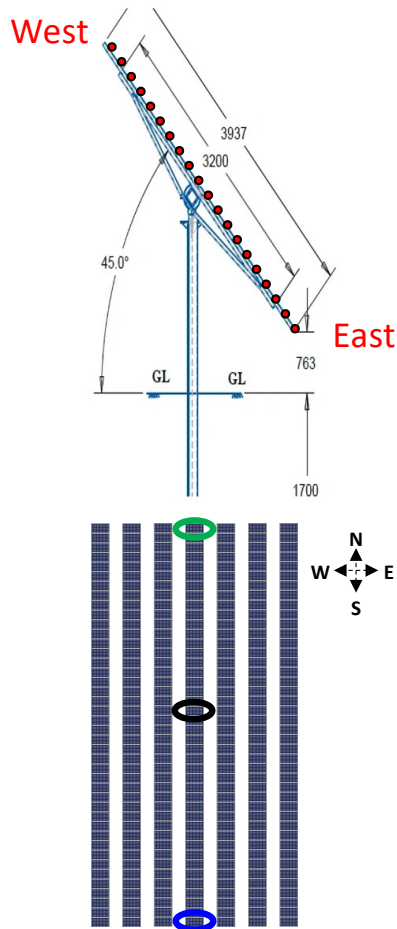
🎯 Worst case difference 7.6%, maximum and minimum points

TOTAL YEARLY RESULTS – CENTER



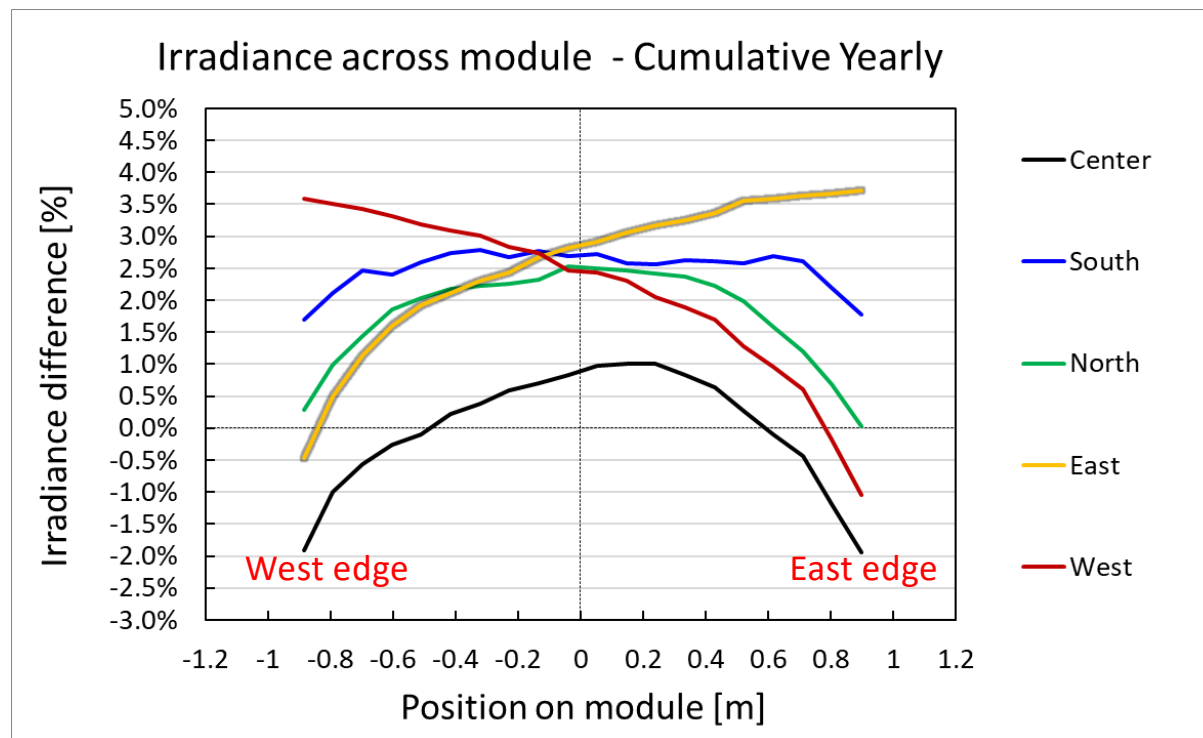
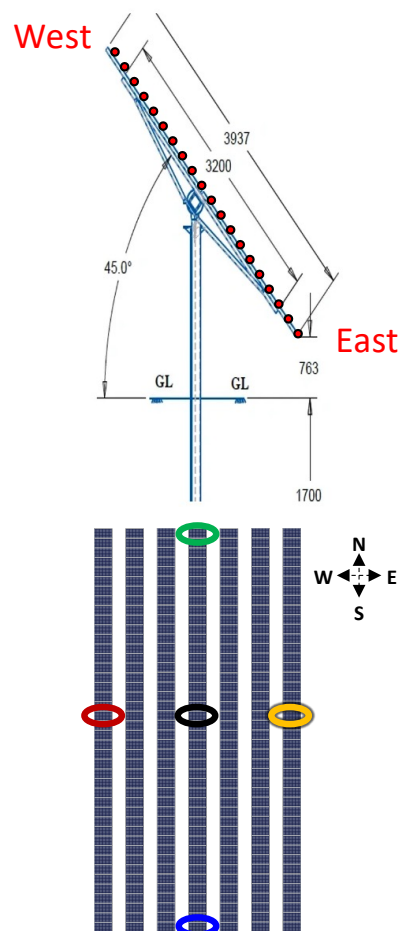
- Each point is compared to the average of all 20 points across the module
- Variation across the center module is roughly 3%

TOTAL YEARLY RESULTS – CENTER



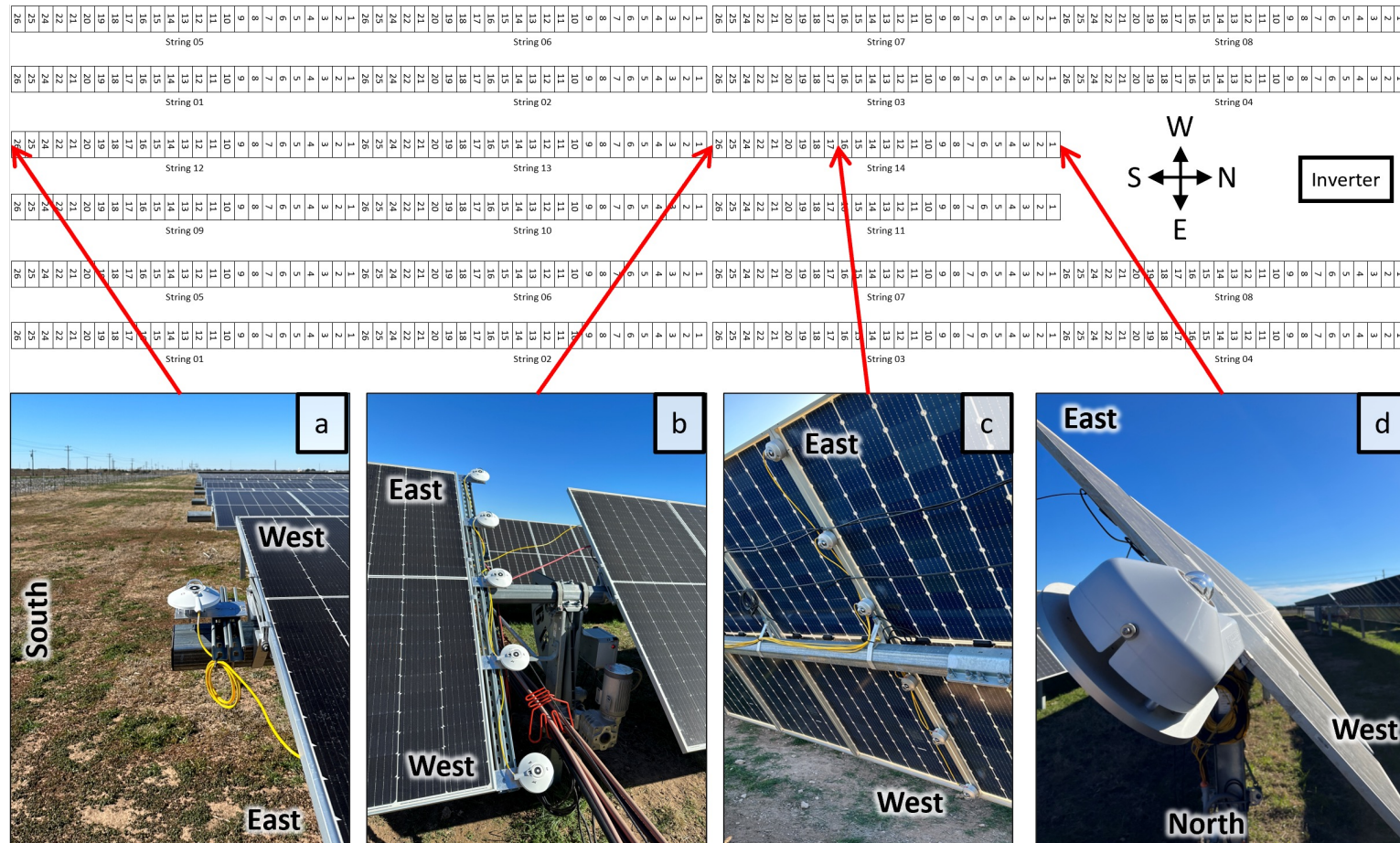
- Each point is compared to the average of all 20 points across the module
- Variation across the north and south module is roughly 2.5% and 1 %

TOTAL YEARLY RESULTS – CENTER

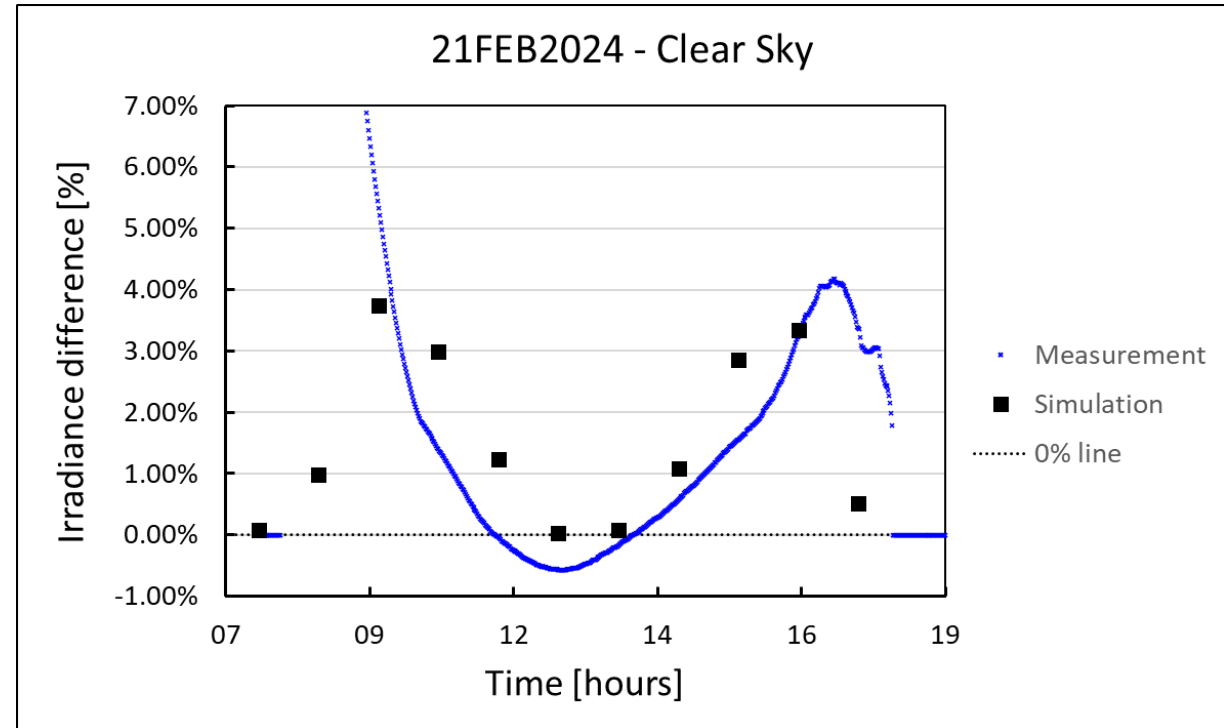
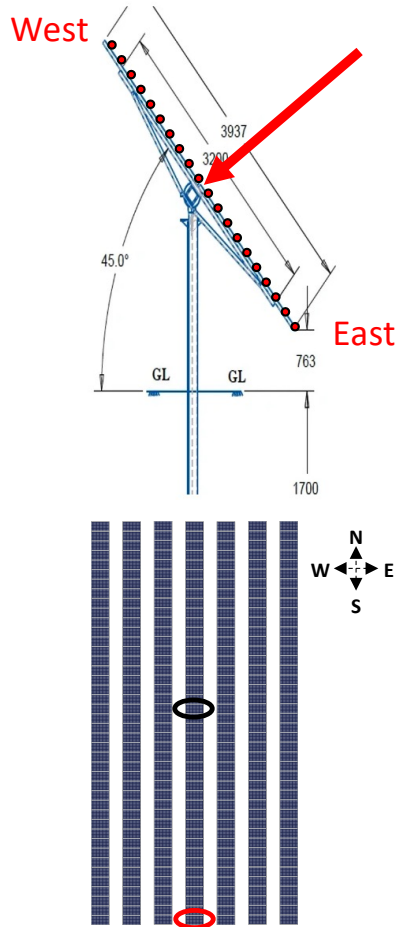


- Each point is compared to the average of all 20 points across the module
- Variation across the east and west module is roughly 3.3% and 4.6%

PV PLANT VALIDATION – SENSOR SETUP

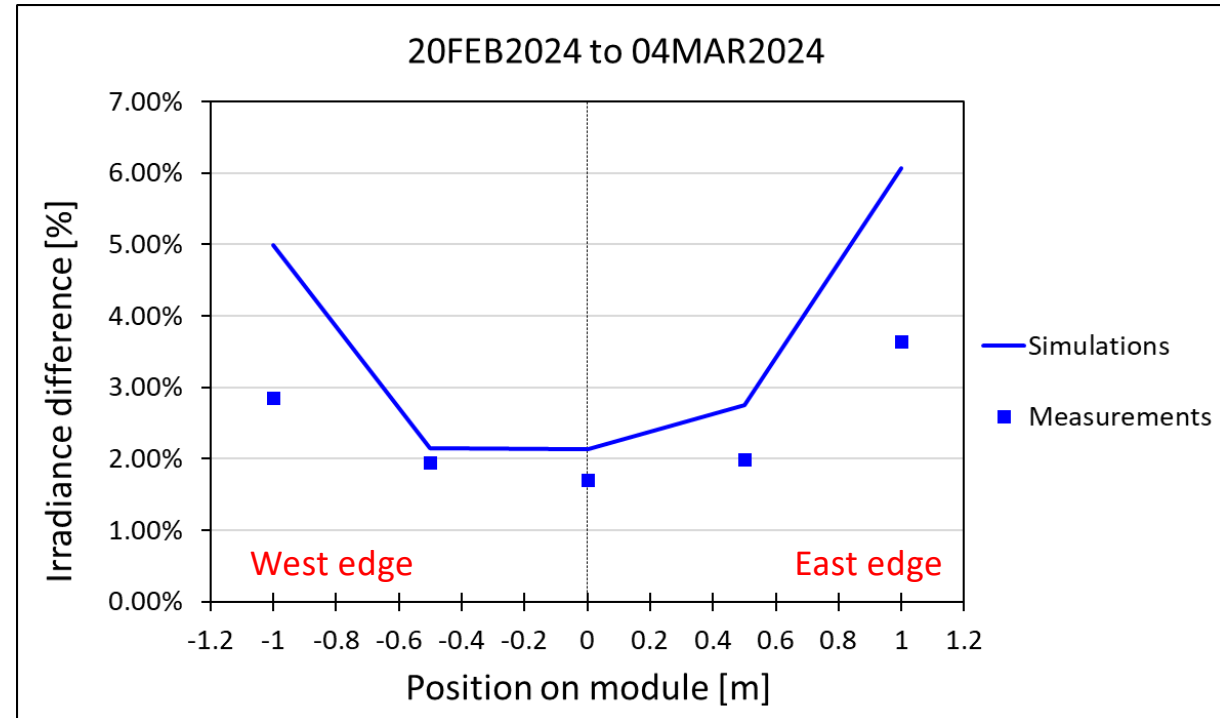
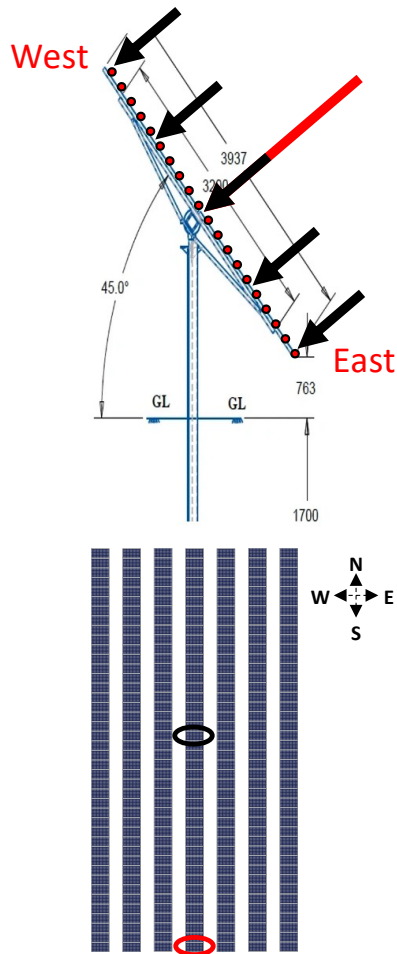


SOUTH-CENTER-MOUNTED, INTRADAY DIFFERENCE



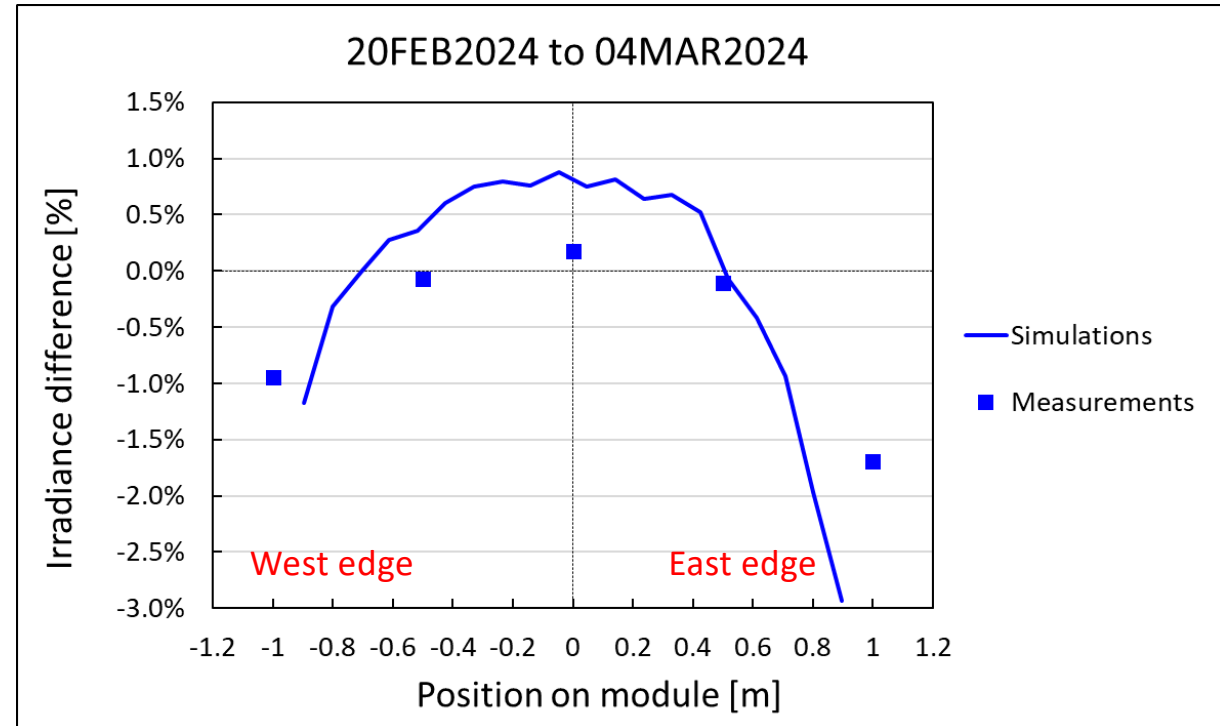
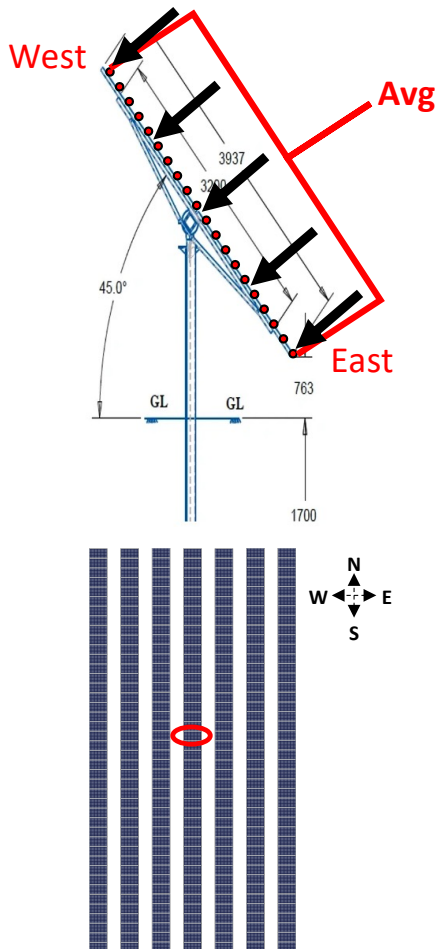
- ⦿ This is a reasonable match between simulations and measurements
- ⦿ Early morning outlier – possibly due to tilt of local module, future work

SOUTH-CENTER vs CENTER, 1.5 MO. DIFFERENCE



- ☉ (South middle) - (Center middle position) = +1.7% (measured), +2.1% (simulation)
- ☉ Maximum measurement pyranometer difference: +3.6% (± 1.8 % uncertainty)

1.5 MONTH CENTER MODULE MEASUREMENTS



- ☉ Difference across module: Simulation: 3.8% Measurement: 1.9%
- ☉ There is a significant effect, however smaller than simulated

CENTER MODULE, INTRADAY AVERAGE

Varying weather conditions

☀ Clear Sky – 14APR2024

☉ Simulations: 0.15%

☉ Measurements: 0.56%

☀ Clear/Cloudy – 02APR2024

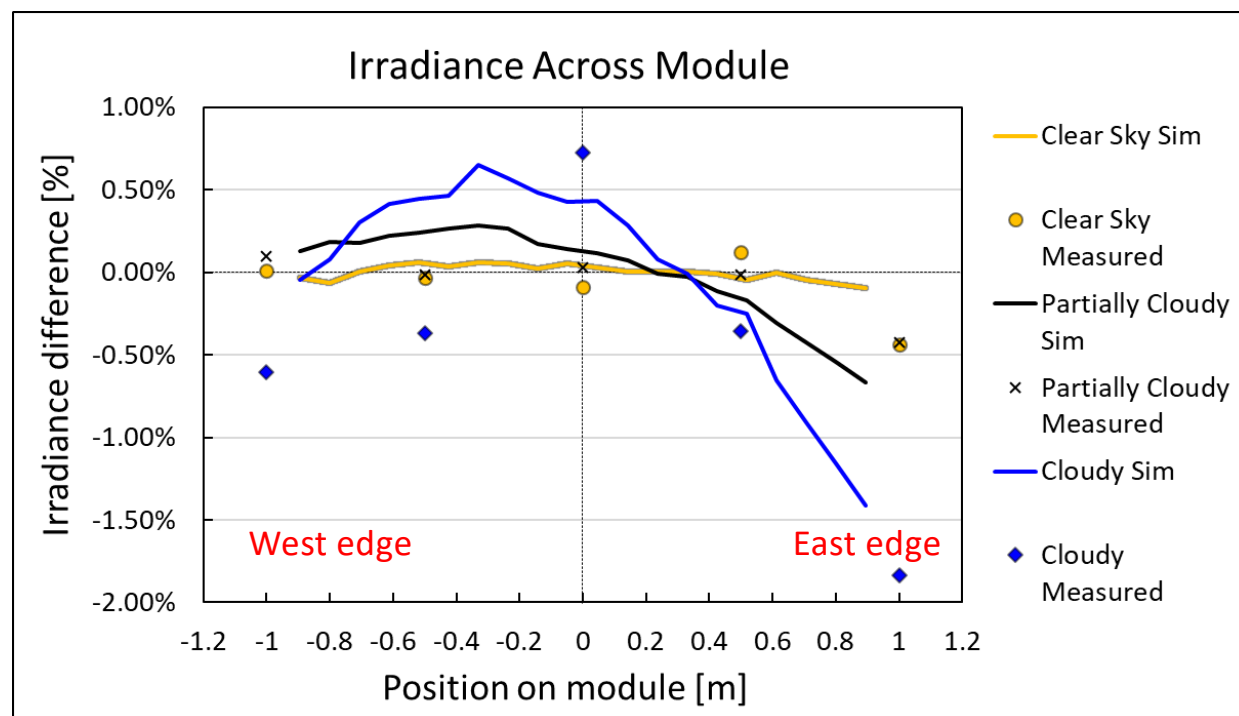
☉ Simulations: 0.95%

☉ Measurements: 0.52%

☁ Cloudy – 15MAR2024

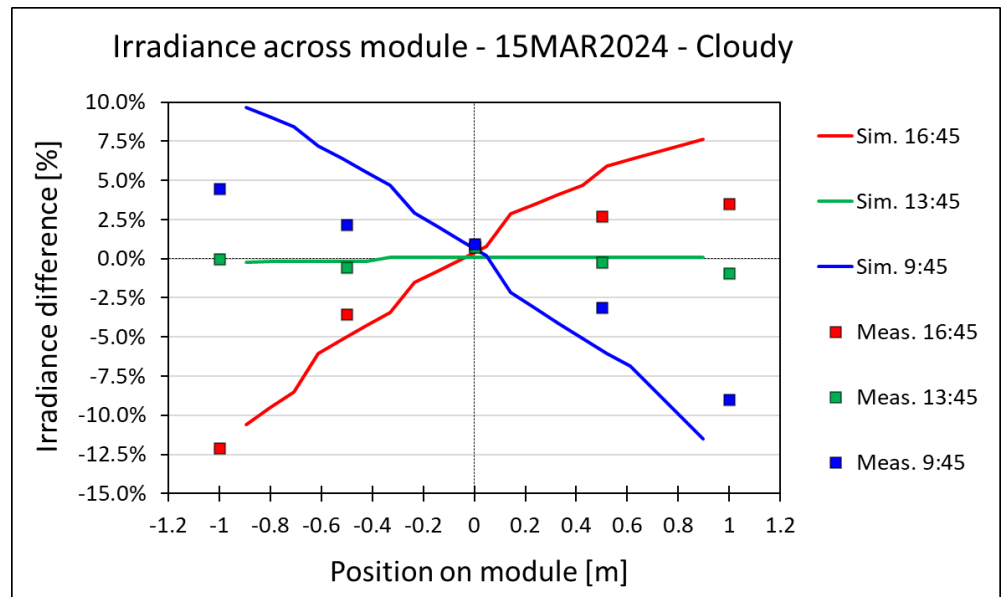
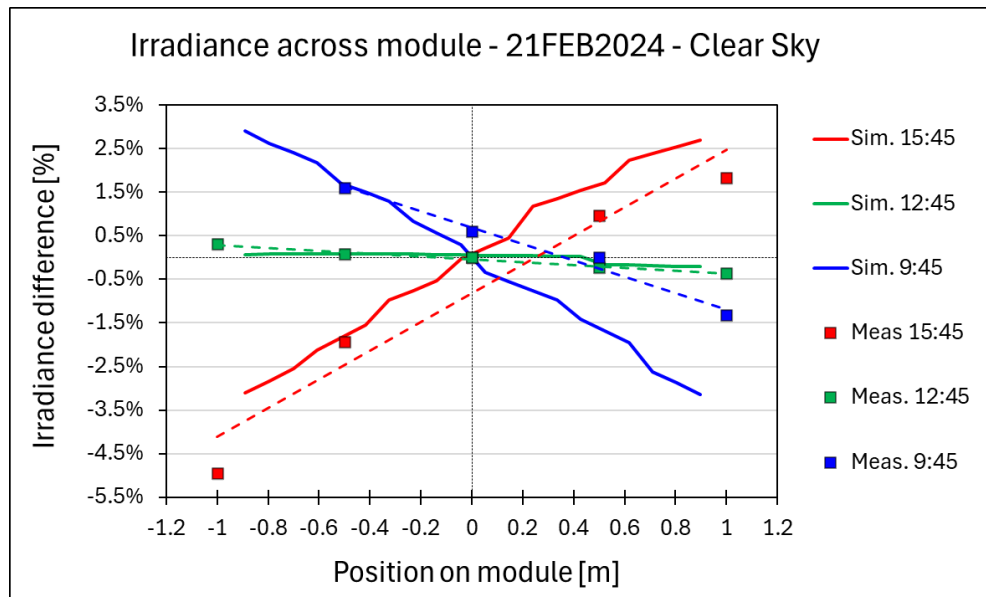
☉ Simulations: 2.06%

☉ Measurements: 2.55 %



CENTER MODULE, INTRADAY HOURLY

Varying weather conditions

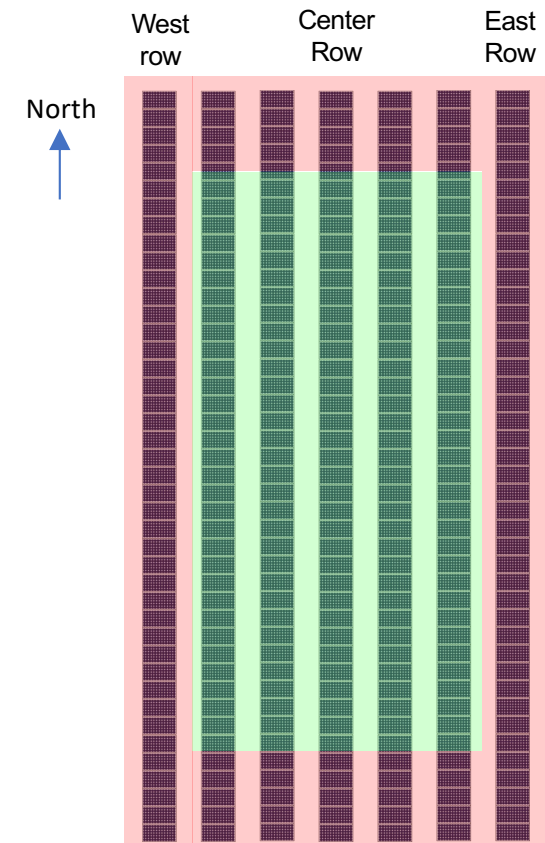


- ☉ Clear Sky (morning) – Simulations: **6%**, Measurements: **7%**
- ☉ Cloudy (afternoon) – Simulations: **21%**, Measurements: **16%**
- ☉ Reasonable agreement of simulations and measurements

CONCLUSIONS

Within the array

- 🎯 Reminder: Accurate sensor, proper install
- 🎯 Sensor siting can artificially increase irradiance, falsely decreasing PR and therefore devaluing the PV park
- 🎯 Differences of siting position within the array:
 - 🕒 Simulations
 - Max. cumulative 1-year error: $\pm 3.8 \%$
 - 🕒 Measurements
 - $\pm 1.8 \%$ over a 1.5-month period (sim.: $\pm 2.9 \%$)
- 🎯 Proposed sensor placement:
 - 🕒 Interior rows (not the east-most or west-most row)
 - 🕒 Away from the row edges
 - > 5 modules into the row



CONCLUSIONS

Across the center-row, center-module

☉ Differences of siting position across the module:

- ☉ Simulations (1-year): $\pm 1.49\%$
- ☉ Simulations (1.5 months): $\pm 1.91\%$
- ☉ Measurements (1.5 months): $\pm 0.94\%$

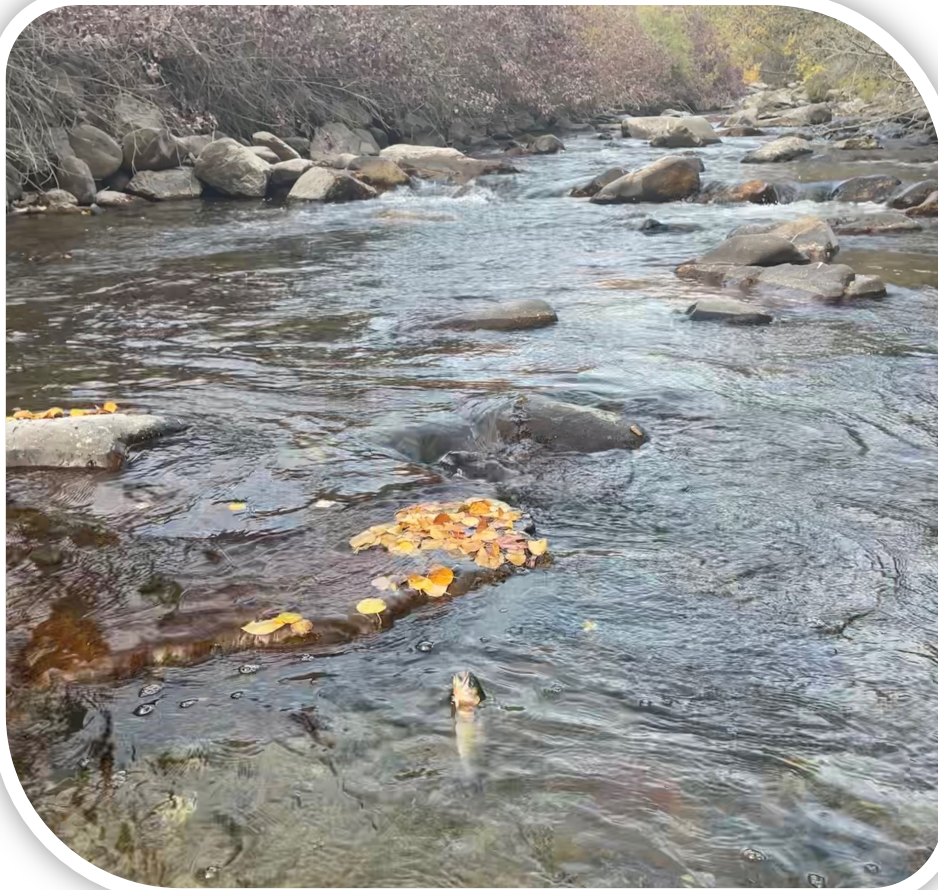
- ☉ Simulations (intraday): $\pm 10.5\%$
- ☉ Measurements (intraday): $\pm 8\%$

☉ Preliminary proposed sensor placement:

- ☉ If (1) sensor, centered on module
 - Difference of 0.7% as measured, and up to 1.0% simulated
- ☉ If (2) sensors, at 25% and 75% of module



CLOSING THOUGHTS



🌀 Acknowledgements:

- 🌀 Merit Controls
 - Nate Solofra
 - Chad Paden
 - Wesley Blanco
- 🌀 Novasource Power
 - Alexander Rangel

THANK YOU

Email: Damon.Nitzel@otthydromet.com

OTT HydroMet product brands



APPENDIX SLIDE(S)

- Simulation parameters

SIMULATION PARAMETERS SINGLE-AXIS TRACKED PLANT

Parameter	Value	Parameter	Value
Hub Height	1.3 m	Module rows	6
Tilt	Backtracking on	Modules per row	80
Azimuth	N-S axis	Number of sensors	20
Ground Coverage Ratio (GCR)	0.48	Location	San Angelo, TX USA
Albedo	0.35	Weather data	Energyplus.net
Module orientation	Portrait	Module dimensions	1.98 m x 0.98 m
Nr. Modules above each other	1	Torque tube	yes
Type of plant	Tracked	Type of simulation	Cumulative sky yearly
Software versions: Python 3.11.5, Radiance 5.3 (2020-09-03), Bifacial radiance V0.4.2 (2023-03-11)[5], PVLIB V0.10.2			

[5] Ayala Pelaez and Deline, (2020). bifacial_radiance: a python package for modeling bifacial solar photovoltaic systems. Journal of Open Source Software, 5(50), 1865, <https://doi.org/10.21105/joss.01865>