DTU

Comparing Different Software Models for Estimating Bifacial Energy Gain

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Support from: EUROPEAN ENERGY, EUDP, COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Comparing Different Software Models for Estimating Bifacial Energy Gain

This presentation is based on the recent publication:

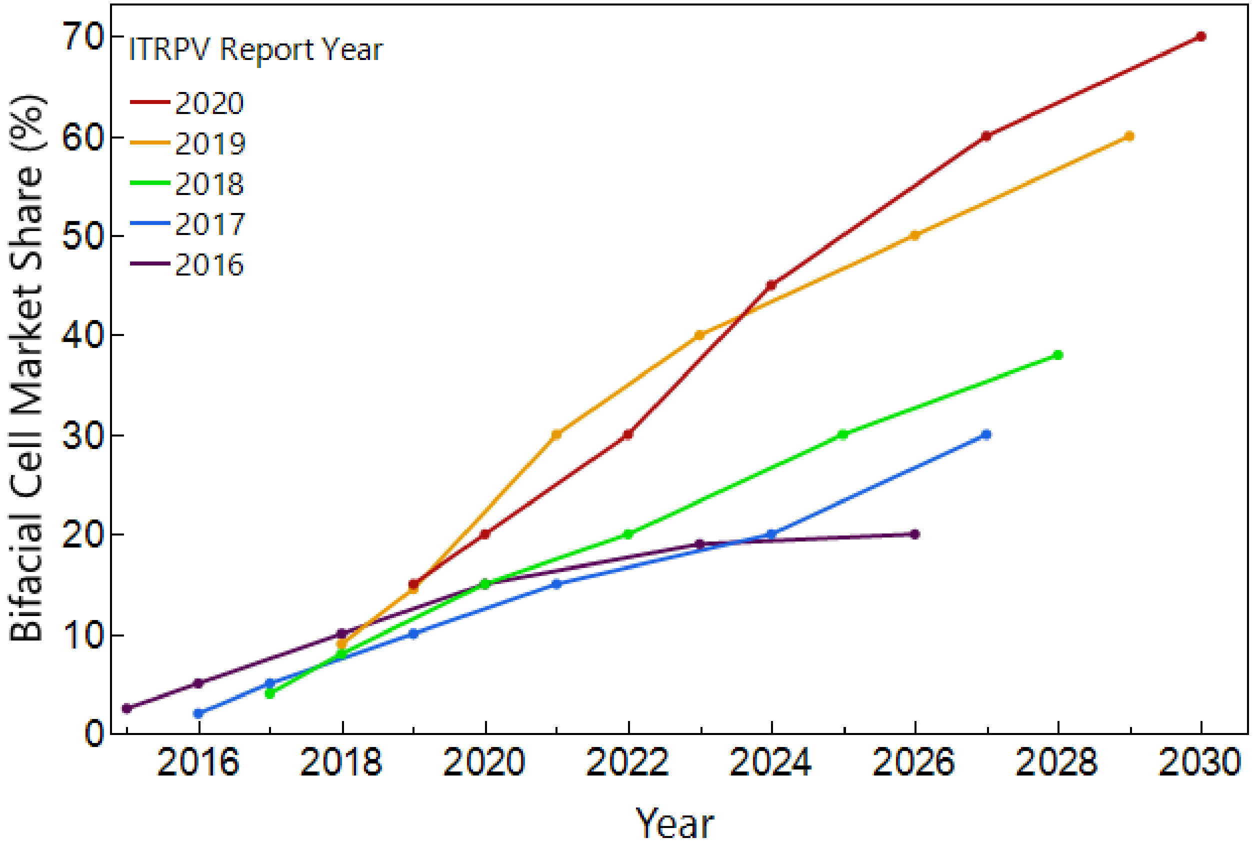
Riedel-Lyngskær et al. Validation of Bifacial Photovoltaic Simulation Software against Monitoring Data from Large-Scale Single-Axis Trackers and Fixed Tilt Systems in Denmark. *Applied Sciences* **2020**, *10*, 8487.

https://www.mdpi.com/2076-3417/10/23/8487

Outline

- Motivation and project background
- Methods
- Results
- Summary

Forecasts for Market Share of Bifacial Cells



Summary of the 10-year forecasts made by ITRPV from 2016-2020

– Each year is increasingly optimistic

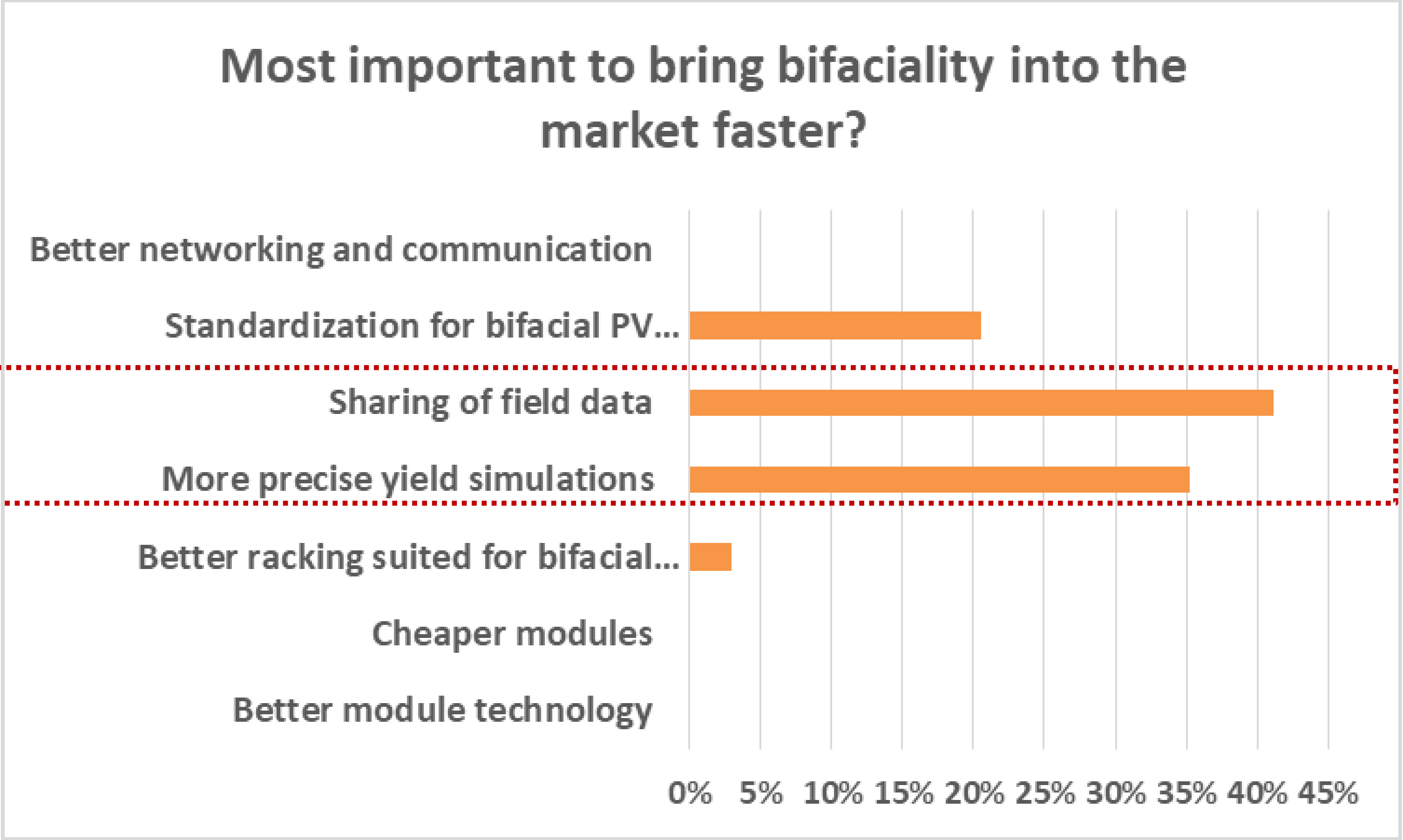
As of 2019, roughly 15% of cells produced were bifacial

– 70% market share in 2030 !

– ITRPV 2021 forecasts???

Digitized from *International Technology Roadmap for PV (ITRPV)* Reports, 2016-2020

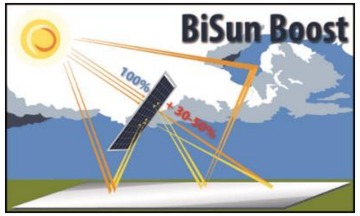
Poll Amongst Participants of the 2018 bifi-PV Workshop



bifi PV workshop 2018 Denver

BiSun Boost Project

EUROPEAN ENERGY



ISC International Solar Energy Research Center Konstanz

DTU

EUDP Contract: 64018-0624

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The Bifacial Test Facility at DTU

Roskilde, Denmark (55.6° N, 12.1° E)

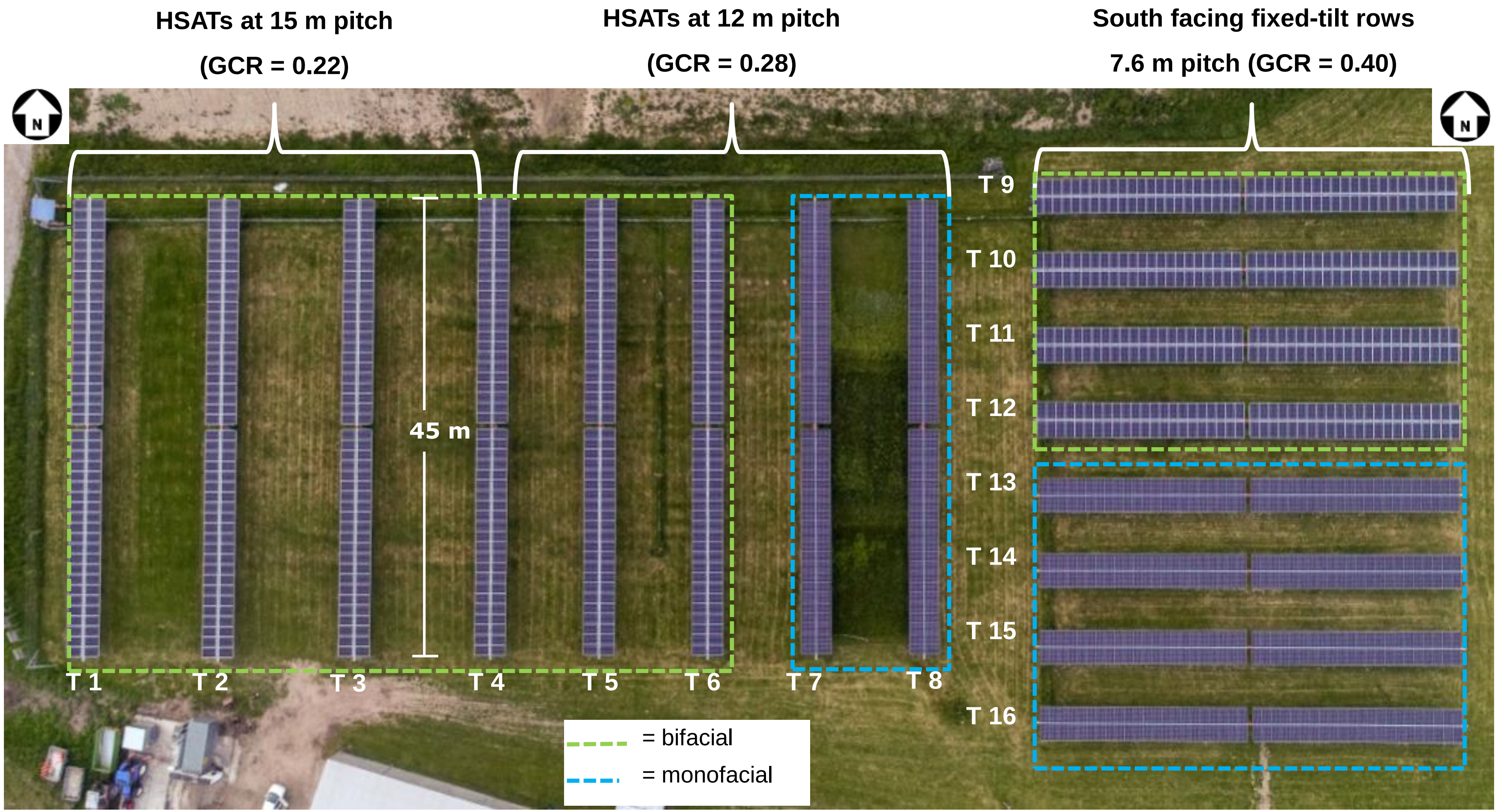
Utility-scale fixed tilts and trackers (HSAT).

Electrical monitoring (I_{MP} and V_{MP}) on 64 strings.

- 1 string = 22 panels
- 4 strings / tracker
- 1 MPPT / tracker

50+ optical sensors in the park

- Pyranometers,
- Reference cells,
- Spectrometers,
- Custom irradiance modules



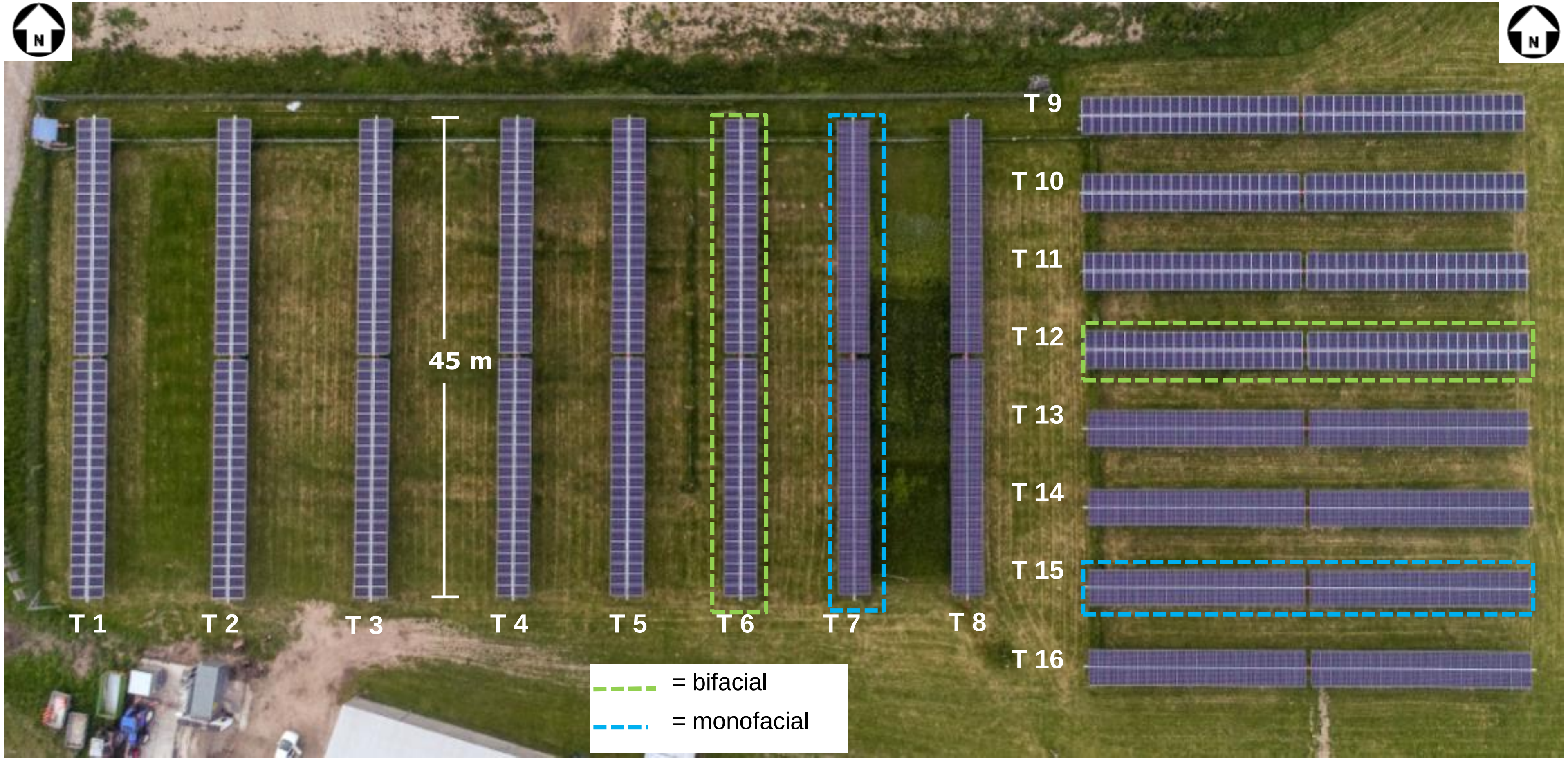
N. Riedel et al., The Outdoor Bifacial Test Facility at DTU, *Bifi PV Workshop*, 2019

Four PV Systems Studied in this Work

This comparison focuses on four individual 26 kWp systems:

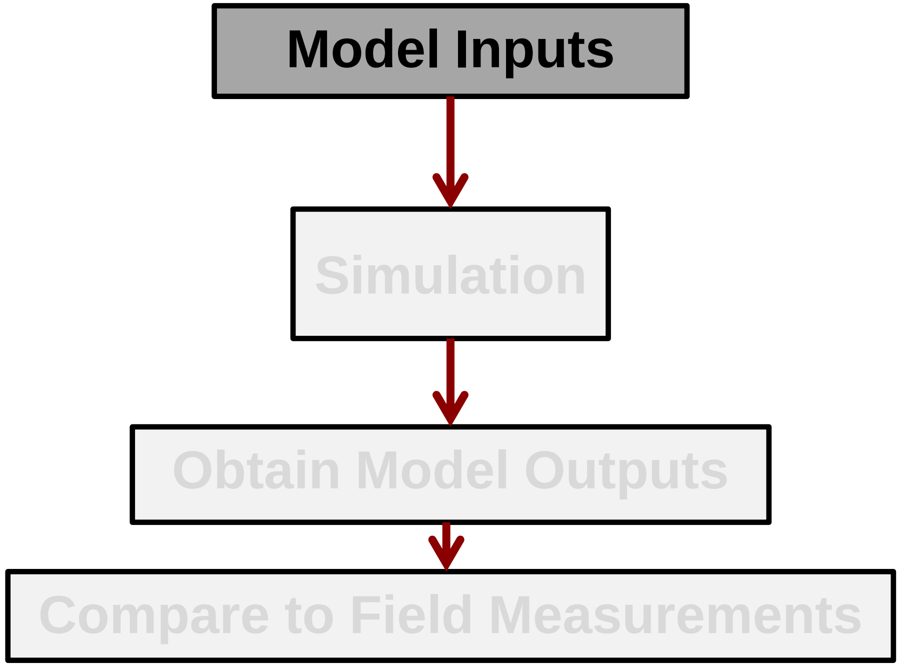
- Bifi HSAT
- Bifi fixed tilt
- Mono-fi HSAT
- Mono-fi fixed tilt

Bifi systems all inner-rows

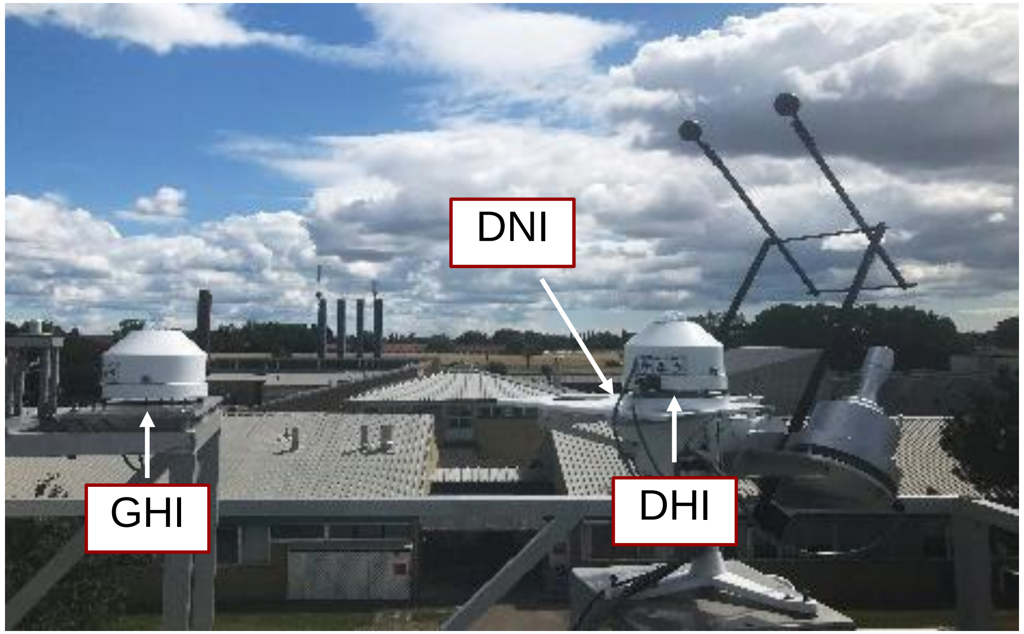


N. Riedel et al., The Outdoor Bifacial Test Facility at DTU, *Bifi PV Workshop*, 2019

Validation Flow Chart



Bifacial Performance Model Validation: Inputs

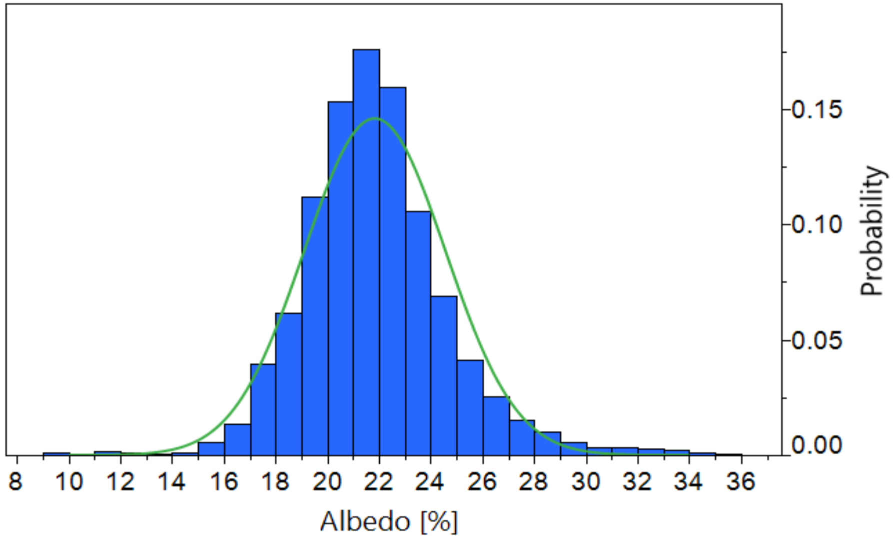


Onsite spectrally flat class A sensors used to create hourly meteo files

- Global (GHI), diffuse (DHI) and beam (DNI)
- Data filtered according to BSRN recommendations*
- Dynamic uncertainty model for each sensor
- Cleaned ~weekly

*Long, C. and Dutton, E. (2010): BSRN Global Network recommended QC tests

Bifacial Performance Model Validation: Inputs



Monthly average albedo used from onsite measurements

- Yearly average = 21.4%
- min. of monthly averages = 19.2%
- max. of monthly averages = 22.9%
- Available on NREL's DuraMat webpage!

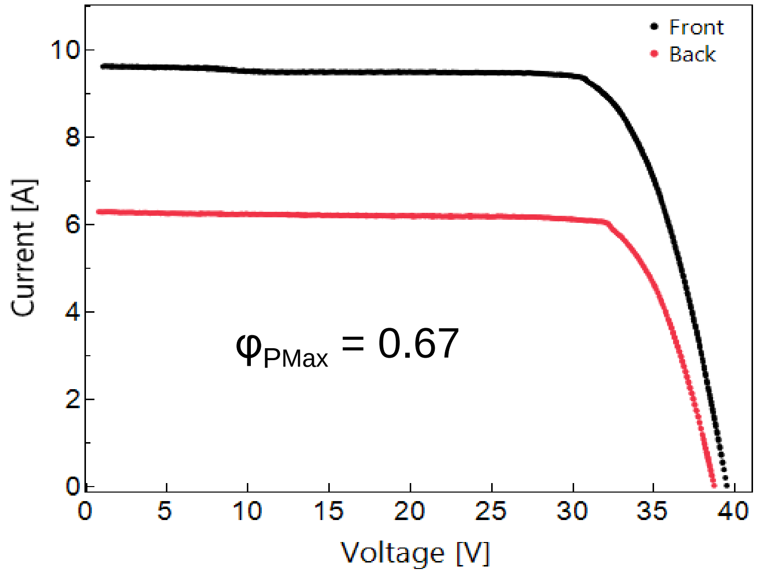
https://datahub.duramat.org/dataset/roskilde-denmark

Bifacial Performance Model Validation: Inputs

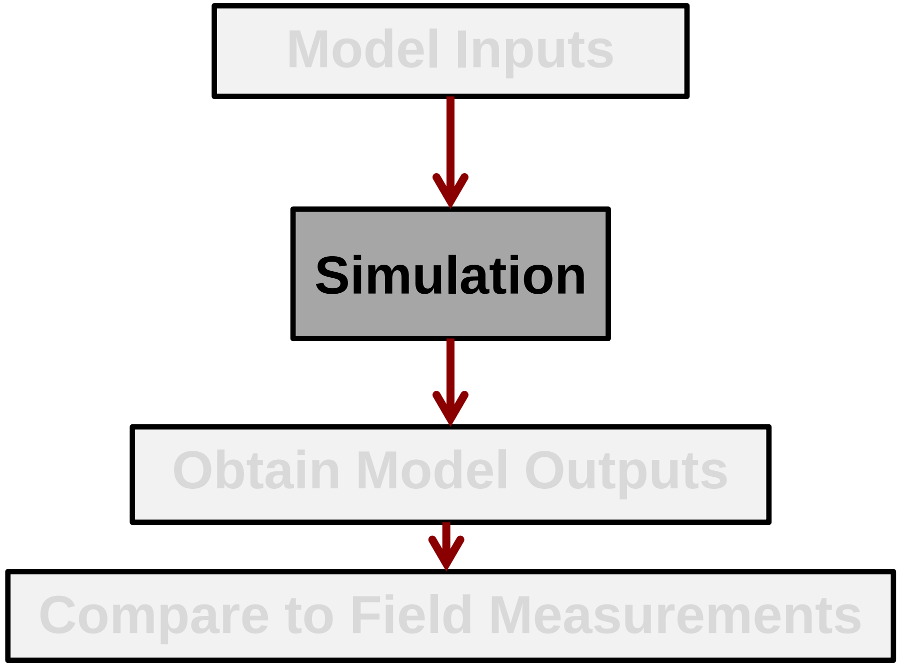
PV electrical parameters determined from indoor I-V measurements at DTU

- Front and back method per IEC 60904-1-2
- Calibration PERC module traceable to Fraunhofer ISE
- Measurements repeated after 1-year to check for LID
    - 1^{st} year $P_{loss} \approx 0.5\%$

PERC⁺ I-V at STC before light exposure



Validation Flow Chart



Bifacial Performance Model Validation: The Software

NREL / bifacialvf

MoBiDiG RT
ISC Konstanz

pvFactors
SunPower

SAM
NREL

PLANTPREDICT
First Solar

MoBiDiG 2DVF
ISC Konstanz

PVsyst

SOLARFARMER
DNV GL

Eight PV Performance Software Sampled for the Comparison

- Includes open-source, freeware, and commercial
- Representative of state-of-the-art bifacial tools used in PV industry and research.

NREL, "bifacialvf," 2019. [Online]. Available: http://github.com/ NREL/bifacialvf.
Berrian, J. Libal and S. Glunz, "MoBiDiG Simulations and LCOE," in *Bifacial Workshop*, Konstanz, 2017
C. Deline and S. Ayala, Bifacial_Radiance. Computer Software. https://github.com/NREL/bifacial_radiance.
M. Anoma et al., "View Factor Model and Validation for Bifacial PV and Diffuse Shade on Single-Axis Trackers," in *44th PVSC*, 2017.
N. Diorio and C. Deline, "Bifacial Simulation in SAM System Advisor Model (SAM)," *Bifacial Workshop* 2018, Denver, USA.
A. Mermoud and B. Wittmer, "Bifacial shed simulation with PVSyst," *Bifacial Workshop 2017, Konstanz, Germany*
M. Mikofski, "SolarFarmer Bifacial Modelling," *PV Systems Symposium 2019, Albuquerque, USA.*

Bifacial Performance Model Validation: The Software

NREL / bifacialvf	MoBiDiG RT ISC Konstanz	pvFactors SunPower	SAM NREL
PLANTPREDICT First Solar	MoBiDiG 2DVF ISC Konstanz	PVsyst PHOTOVOLTAIC SOFTWARE	SOLARFARMER PV plant modelling DNV GL

Eight PV Performance Software Sampled for the Comparison

- **Seven 2D View Factor (VF) models, one 3D Ray Trace (RT) model.**
- Rear irradiance calculated with **simplified** vs. **complex** geometries

Bifacial Performance Model Validation: The Software

NREL / bifacialvf	MoBiDiG RT ISC Konstanz	pvFactors SunPower	SAM NREL
PLANTPREDICT First Solar	MoBiDiG 2DVF ISC Konstanz	PVSYST PHOTOVOLTAIC SOFTWARE	SOLARFARMER PV plant modelling DNV GL

Eight PV Performance Software Sampled for the Comparison

- **Six include optical, thermal and electrical models, two are only an optical model.**

Bifacial Performance Model Validation: The Software

NREL / bifacialvf

MoBiDiG RT
ISC Konstanz

pvFactors
SunPower

SAM
NREL

PLANT PREDICT
First Solar

MoBiDiG 2DVF
ISC Konstanz

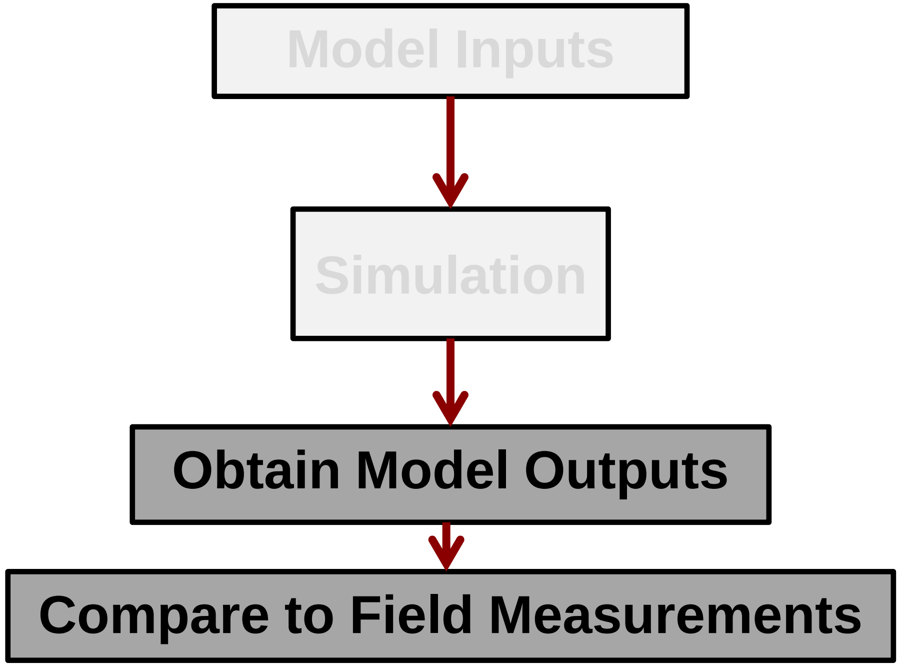
PVsyst
PHOTOVOLTAIC SOFTWARE

SOLARFARMER
PV plant modelling
DNV GL

Differences are expected at key steps of the modeling chain!

- Transposition uses either GHI and DHI, or, DNI and DHI,
- 3 different solar position algorithms used,
- 4 different IAM models used,
- 2 different thermal models used,
- 2 different electrical models used

Validation Flow Chart



Bifacial Performance Model Validation: Field Measurements

Backside POA

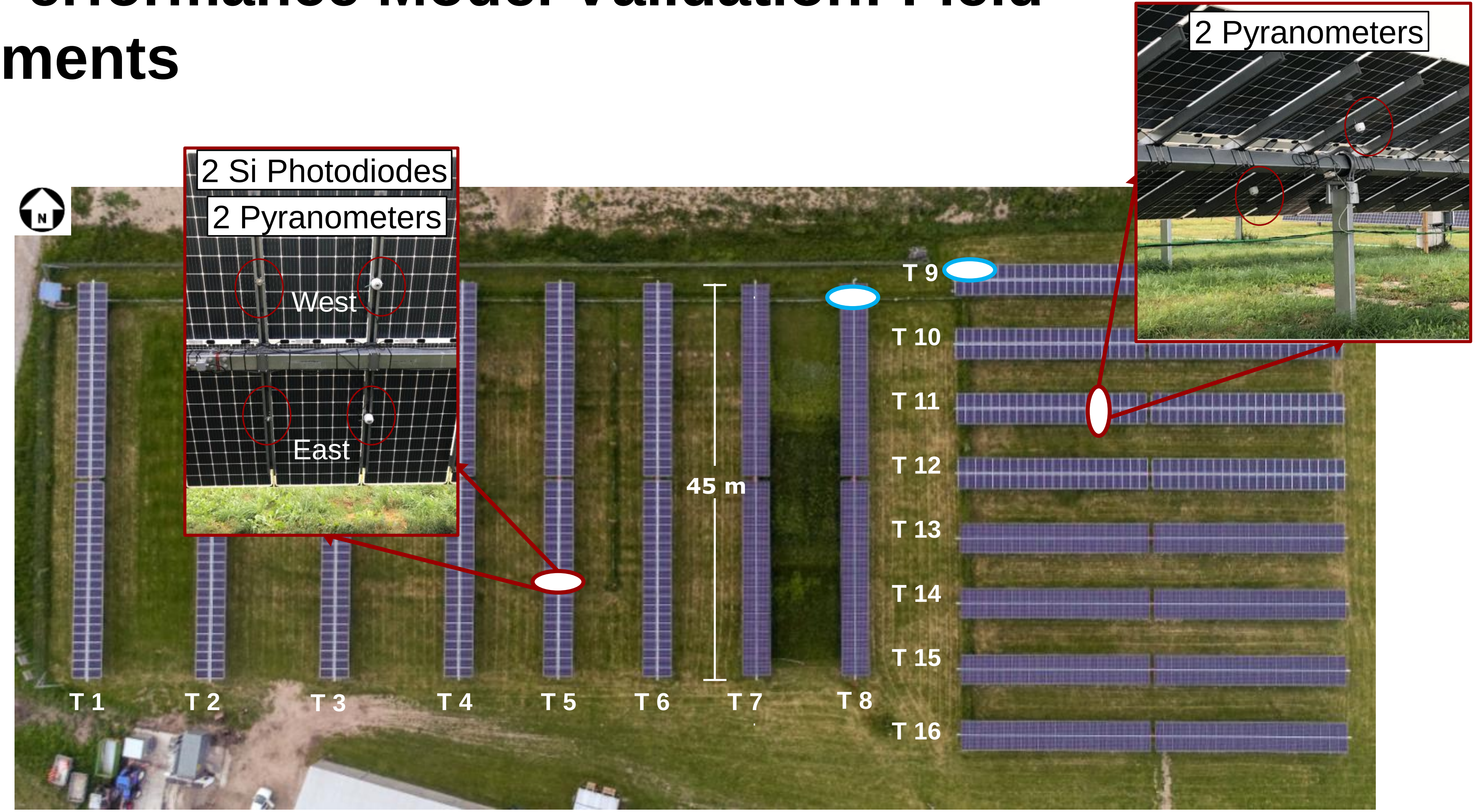
Frontside POA

DC P_{MAX}

- Each string
- independent of inverter

Tmod

- Monofacial only



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Rear POA Irradiance Cross Comparison

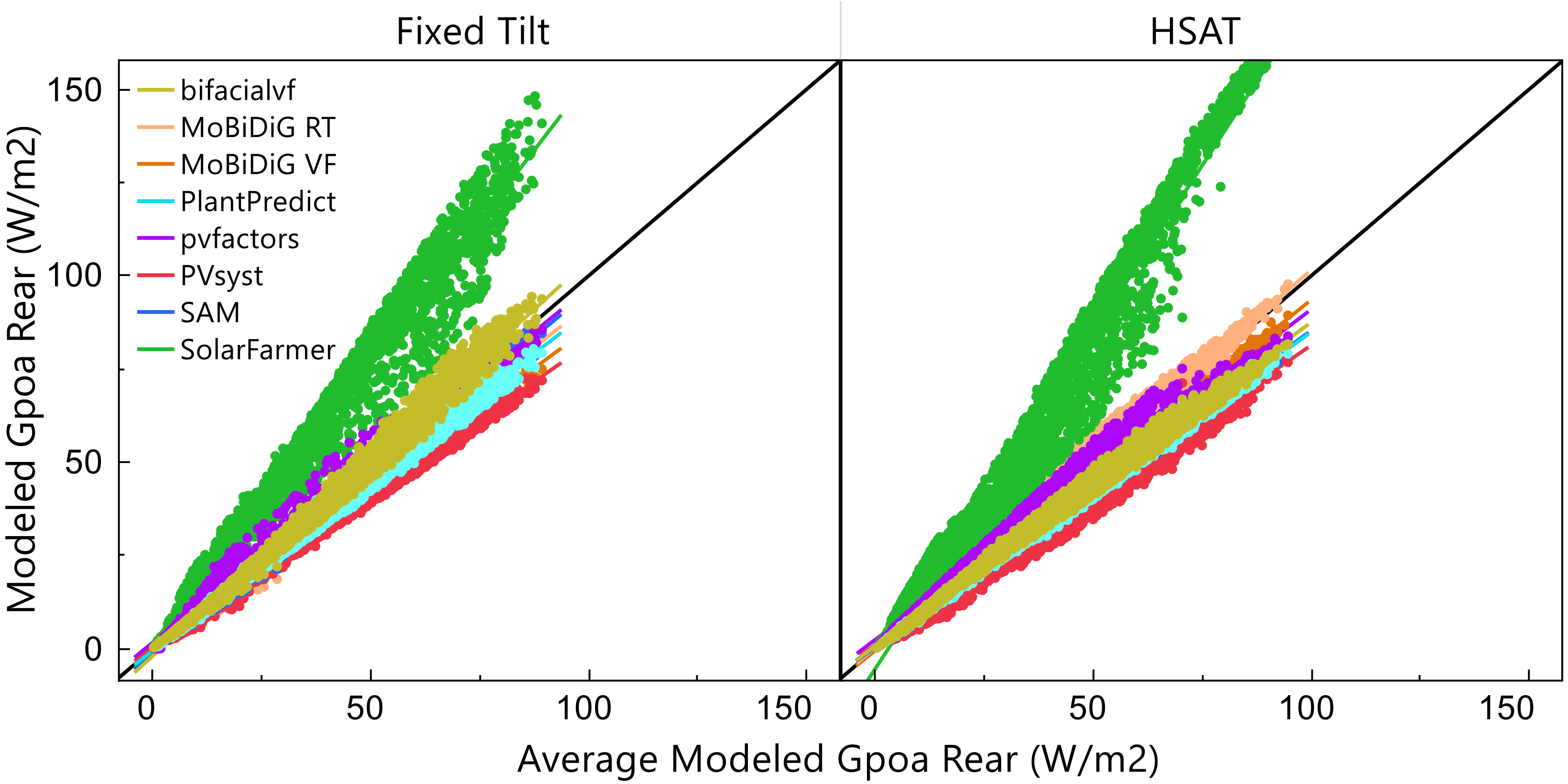
12 months of simulated rear POA irradiance using inputs and parameters from the DTU site

Range of modeled rear G_{POA} values correlates w/ frontside G_{POA}

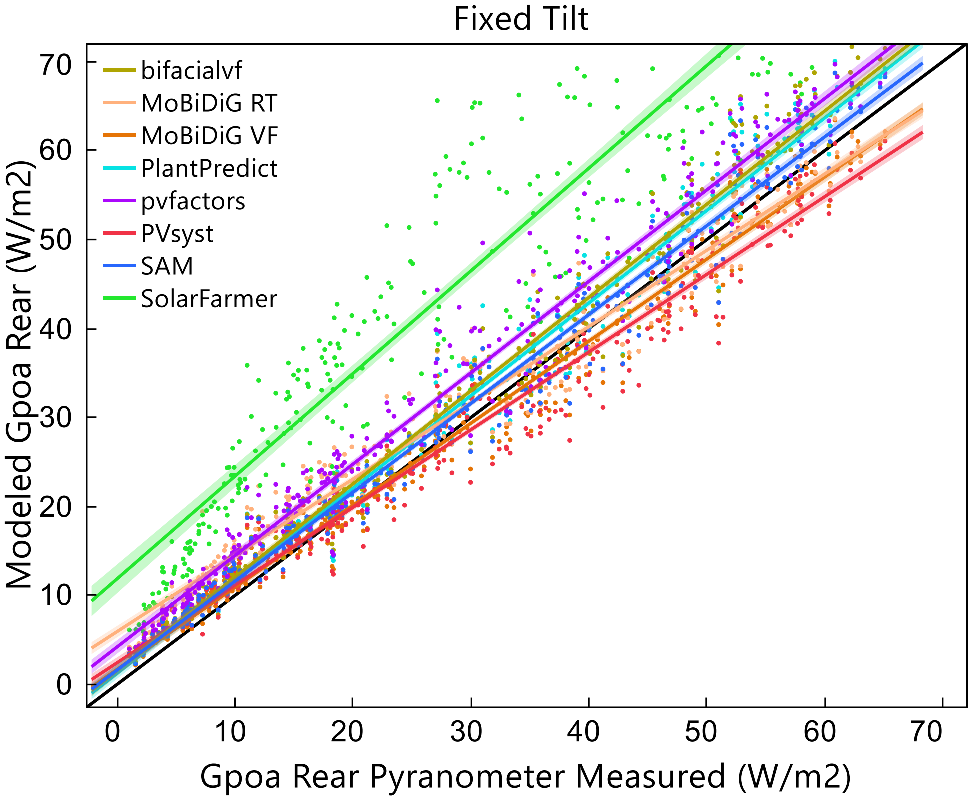
- 20 W/m^2 range at 1000 W/m^2

SolarFarmer does not consider the obstruction of the $VF_{sky\text{->}ground}$ from neighboring rows.

- Currently under revision



Rear POA Irradiance Comparison to Measurements: Fixed Tilt System



6 of 7 2DVF model trendlines agree well to pyranometer measurements

- MAE 2.3 W/m^2 – 5.2 W/m^2
- Results in about 0.5% added uncertainty in the PV modeling chain due to backside irradiance.

Measurements shown are from 1 month of averaged hourly readings from two pyranometers (top and bottom)

Model	MAE [W/m2]	RMSE [W/m2]
bifacialvf	3.4	4.3
MoBiDiG RT	3.8	4.4
MoBiDiG VF	2.3	3.0
PlantPredict	2.9	3.8
pvfactors	5.2	6.1
PVsyst	3.0	3.8
SAM	2.6	3.3
SolarFarmer	16.2	18.1

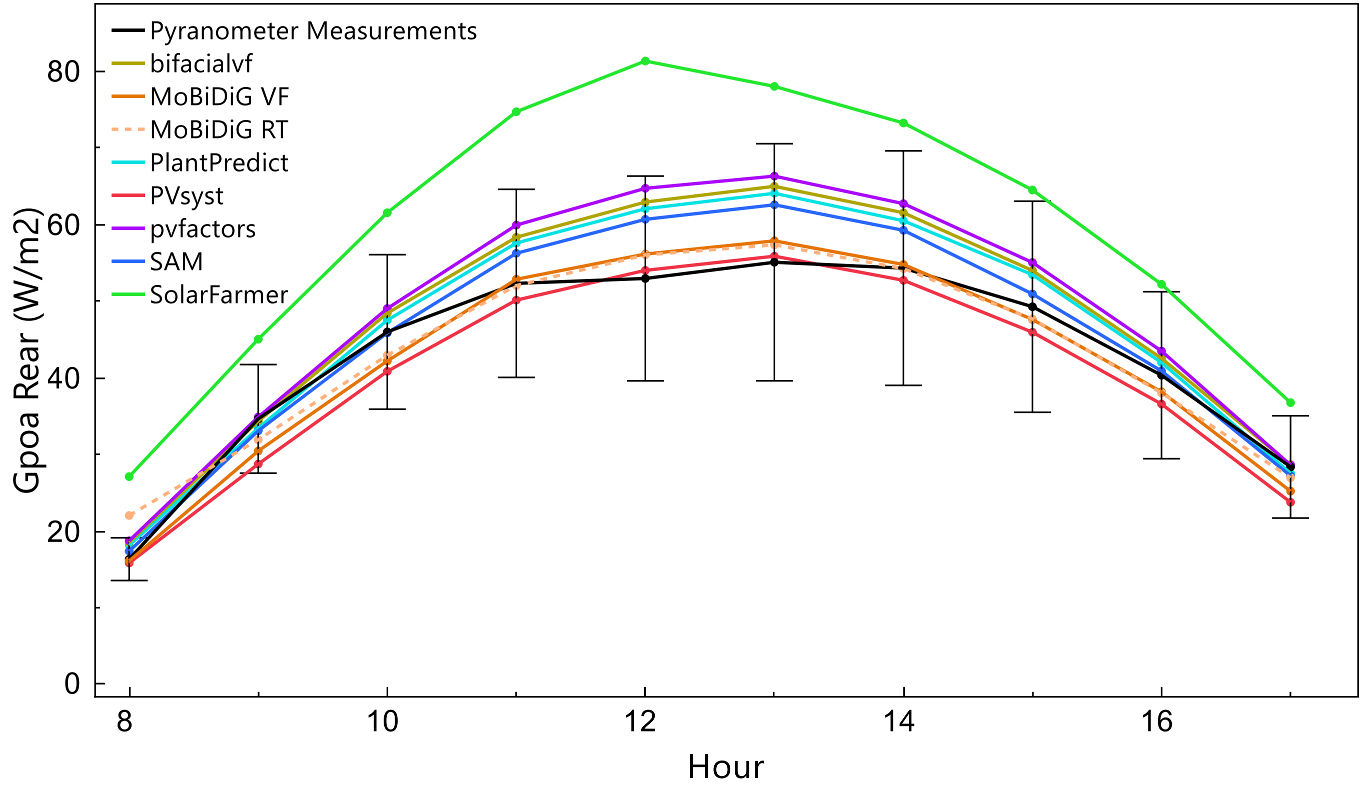
Rear POA Irradiance Timeseries Comparisons: Fixed Tilt System

Data from a clear-sky day in late March

Black line is the average of two pyranometer measurements

Error bars constructed from measurement range (top and bottom pyranometers)

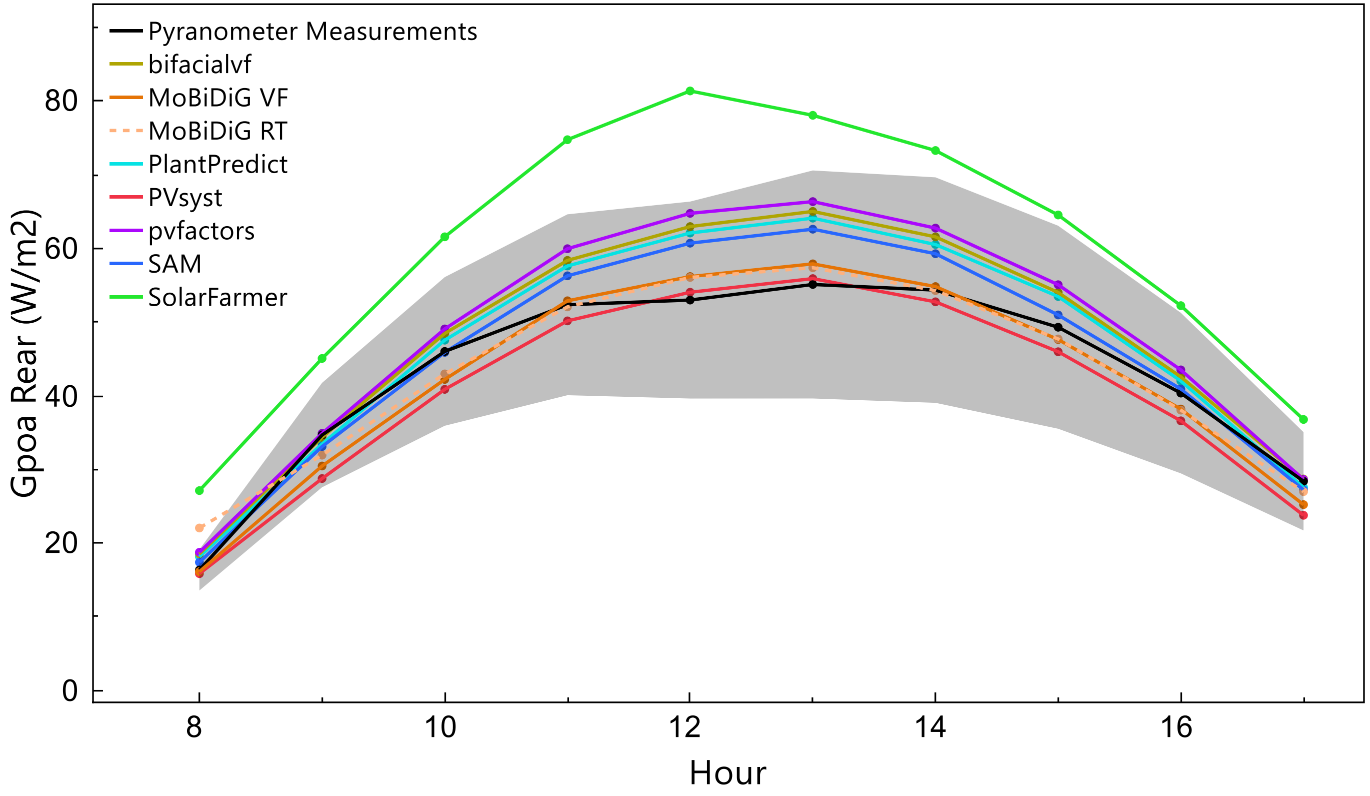
Bottom sensor receives up to 2x the irradiance as top sensor, under clear skies



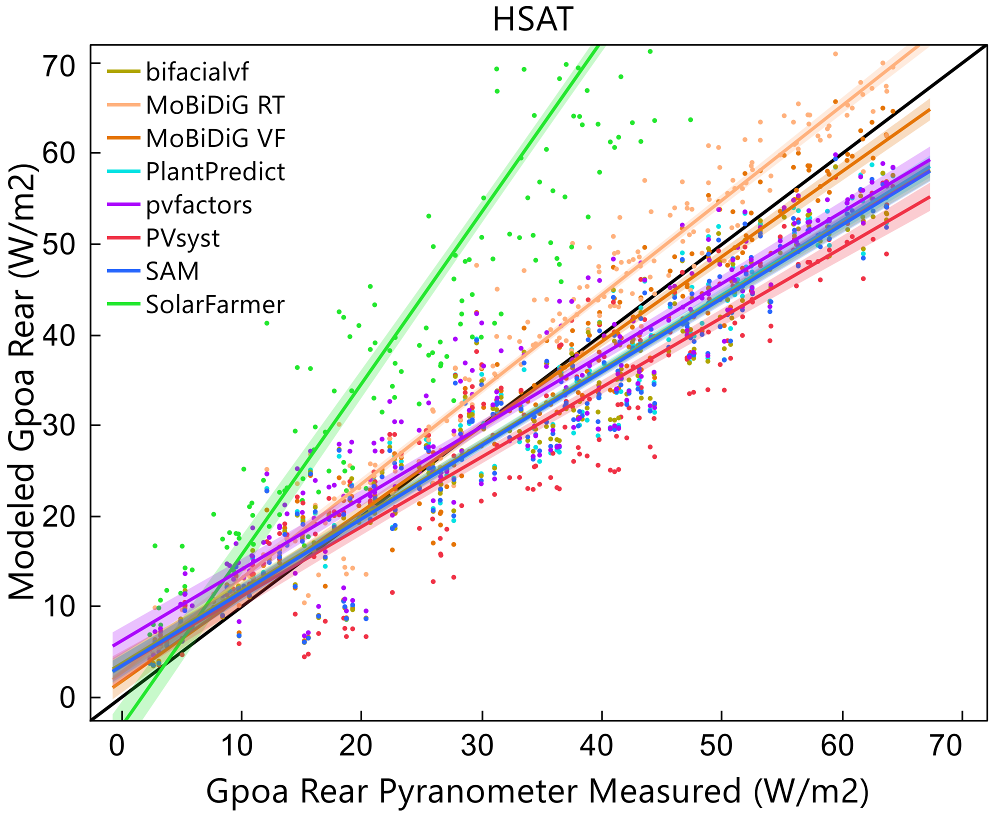
Rear POA Irradiance Timeseries Comparisons: Fixed Tilt System

When the spatial non-uniformity is considered, 7 of 8 software predict rear irradiance on the fixed system reasonably well.

25° Fixed Tilt System



Rear POA Irradiance Comparison to Measurements: Single Axis Tracker



Less accuracy than fixed tilt simulations

- Tracker algorithm/dynamic VFs

4 of 7 2DVF model trendlines agree well to each other

1 2DVF model trendline agrees well to measurements

VF Simulations tend to under predict measurements

Model	MAE [W/m2]	RMSE [W/m2]
bifacialvf	4.8	5.8
MoBiDiG RT	4.8	5.6
MoBiDiG VF	3.5	4.3
PlantPredict	4.9	5.8
pvfactors	5.4	6.1
PVsyst	6.7	7.9
SAM	4.8	5.8
SolarFarmer	27.5	32.5

Electrical Gains: Simulated vs. Measured

$$BG\ (\%) = \left(\frac{E_{BF}/P_{STC,BF}}{E_{MF}/P_{STC,MF}} - 1 \right) \cdot 100$$

E_{BF} = Monthly energy from bifacial

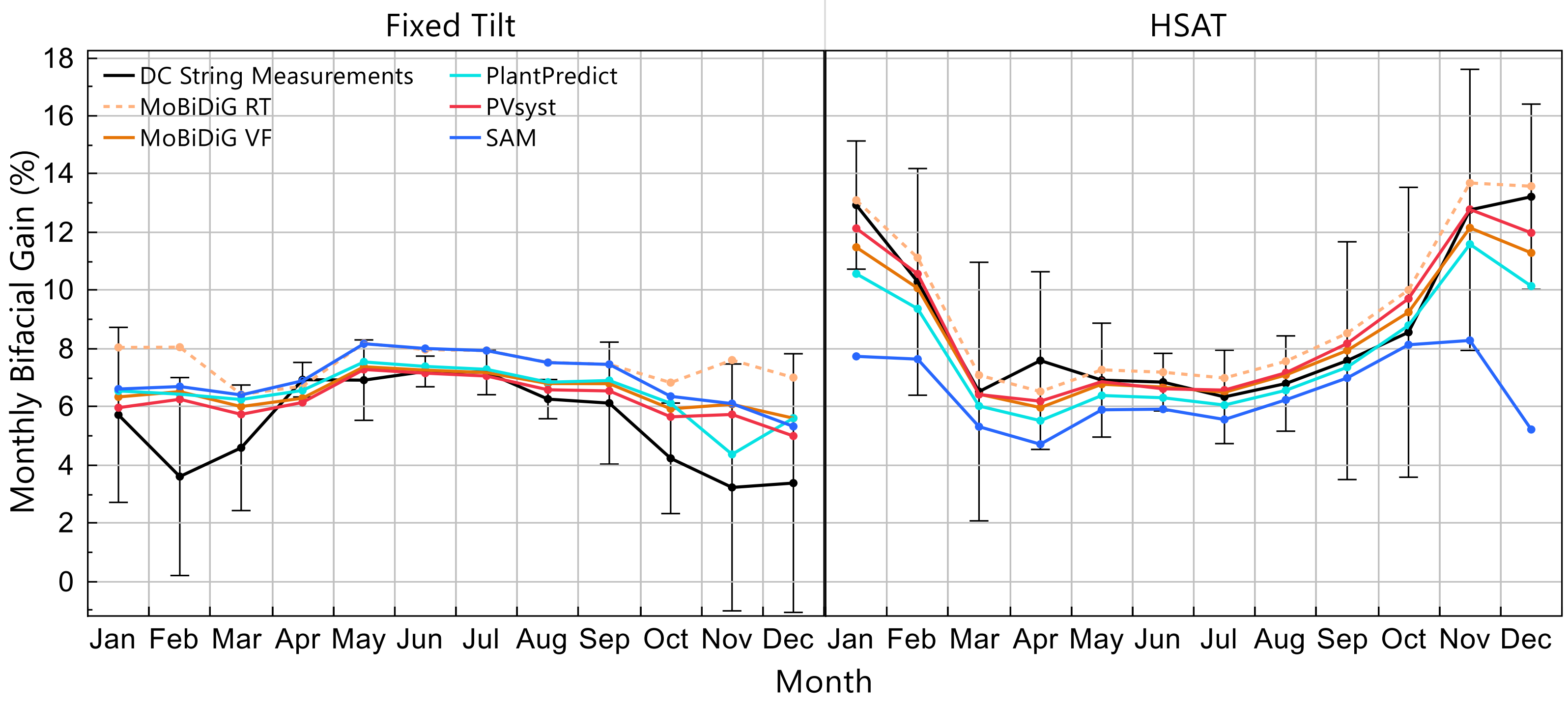
E_{MF} = Monthly energy from monofacial

$P_{STC,BF}$ = Frontside bifi Pmax from DTU I-V

$P_{STC,MF}$ = Monofacial Pmax from DTU I-V

This plot only shows results from 5 software that use an electrical model

Bifacial gain is 1.5% higher when normalized to nameplate data



Electrical Gains: Simulated vs. Measured

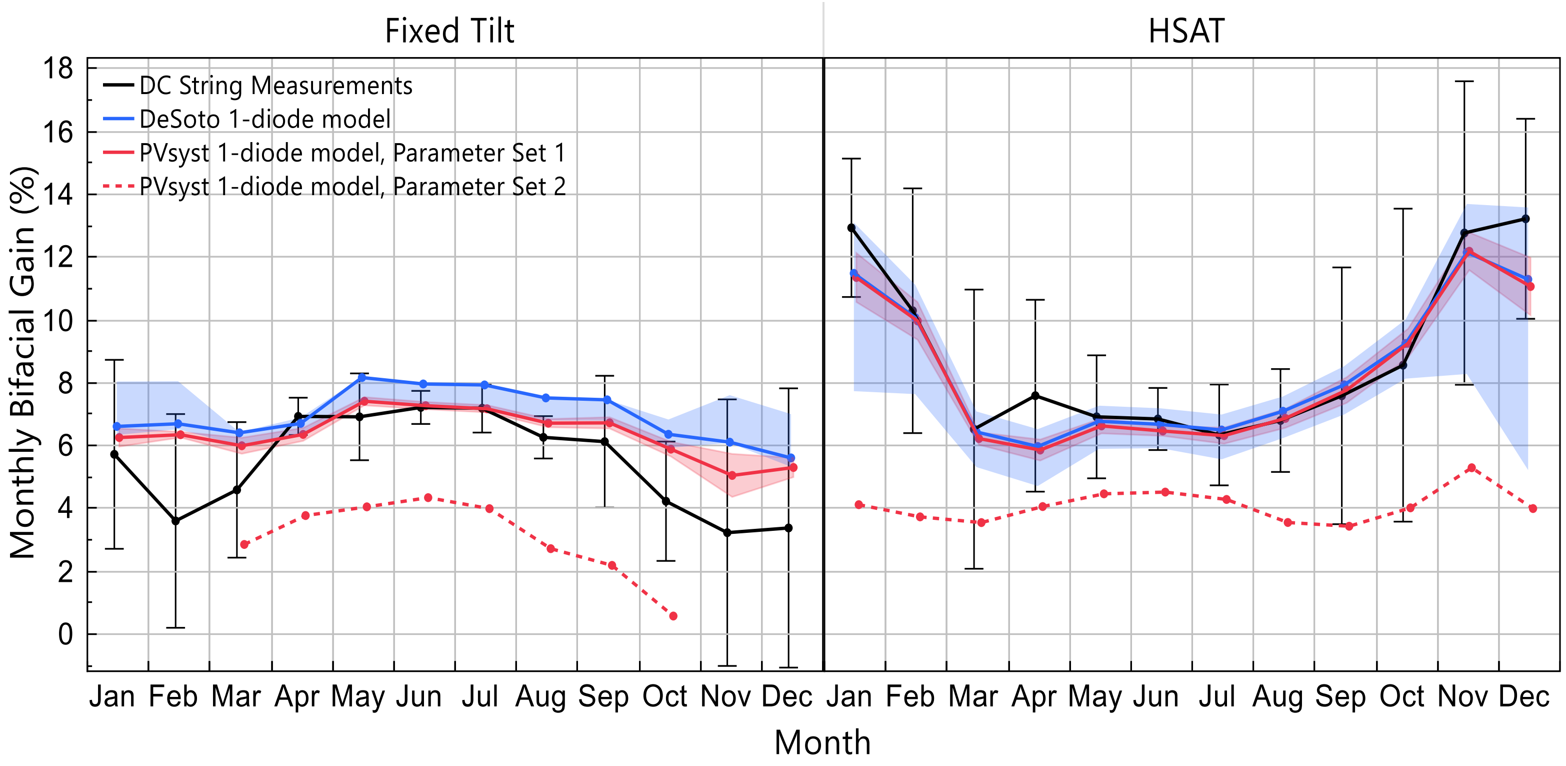
The electrical model – and parameter values used – influences the results

Low light performance varies between the DeSoto and PVsyst models implemented here.

- Param. set 1 uses multi-G IV
- Param. set 2 uses only STC IV

Fixed tilt agreement not great in winter, likely due to greater shading on bifacial vs fixed tilt arrays.

- Bifacial arrays have torque tube gap
- Monofacial array have no such gap



Simulated Optical Gains vs. Measured Electrical Gains

$$BG\ (\%) = \frac{Grear}{Gfront} \cdot BF \cdot (1 - Bifi_{loss}) \cdot 100$$

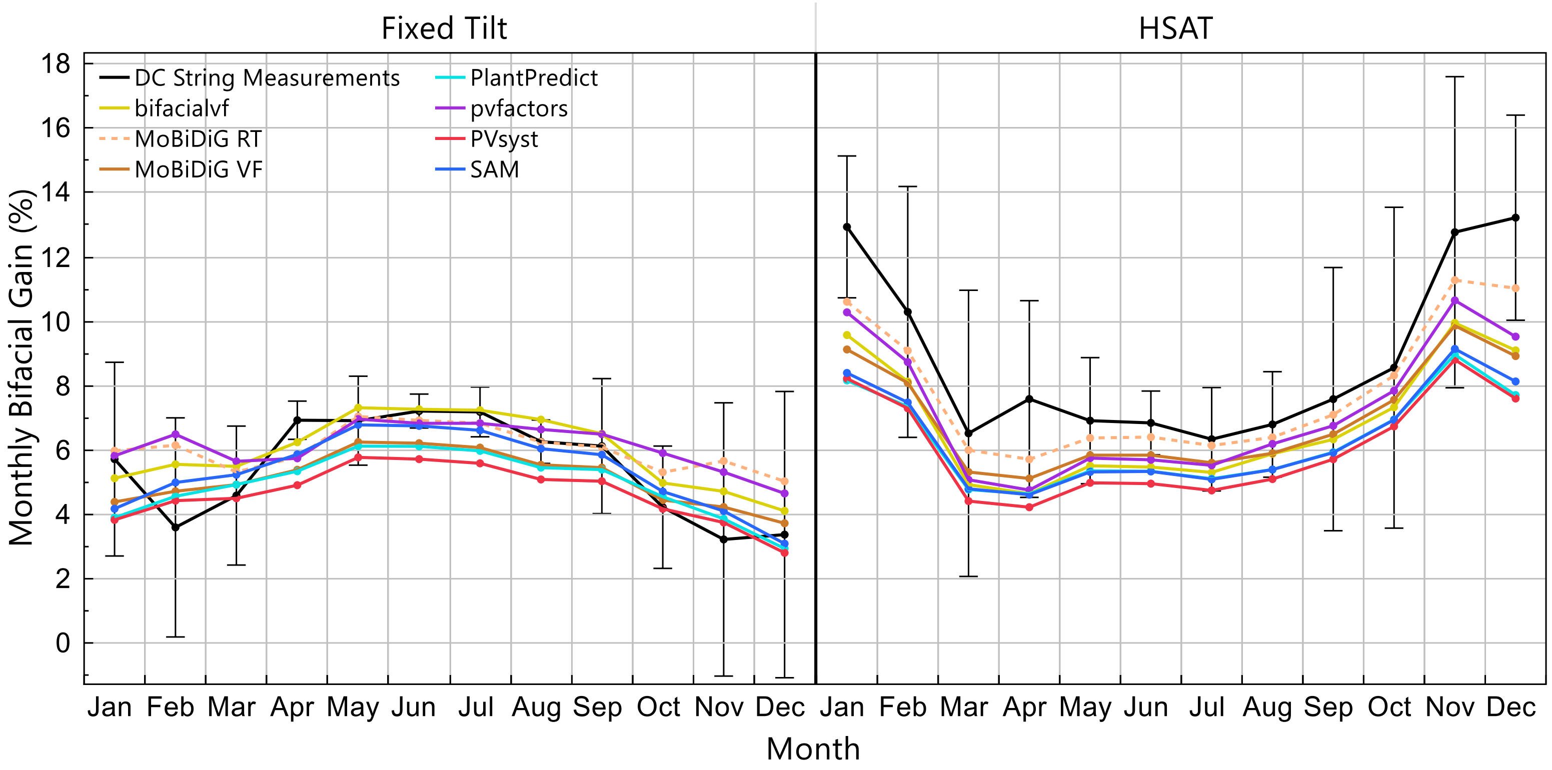
G_{front} = Front POA irradiance

G_{rear} = Rear POA irradiance

BF = Bifaciality at STC (0.67)

$Bifi_{loss}$ = Structural shade losses (0.032)*

The results from 7 software are compared here



*N. Riedel-Lyngskær et al., A Spatial Irradiance Map Measured on the Back of a Horizontal Single-Axis Tracker, PVSC 2020

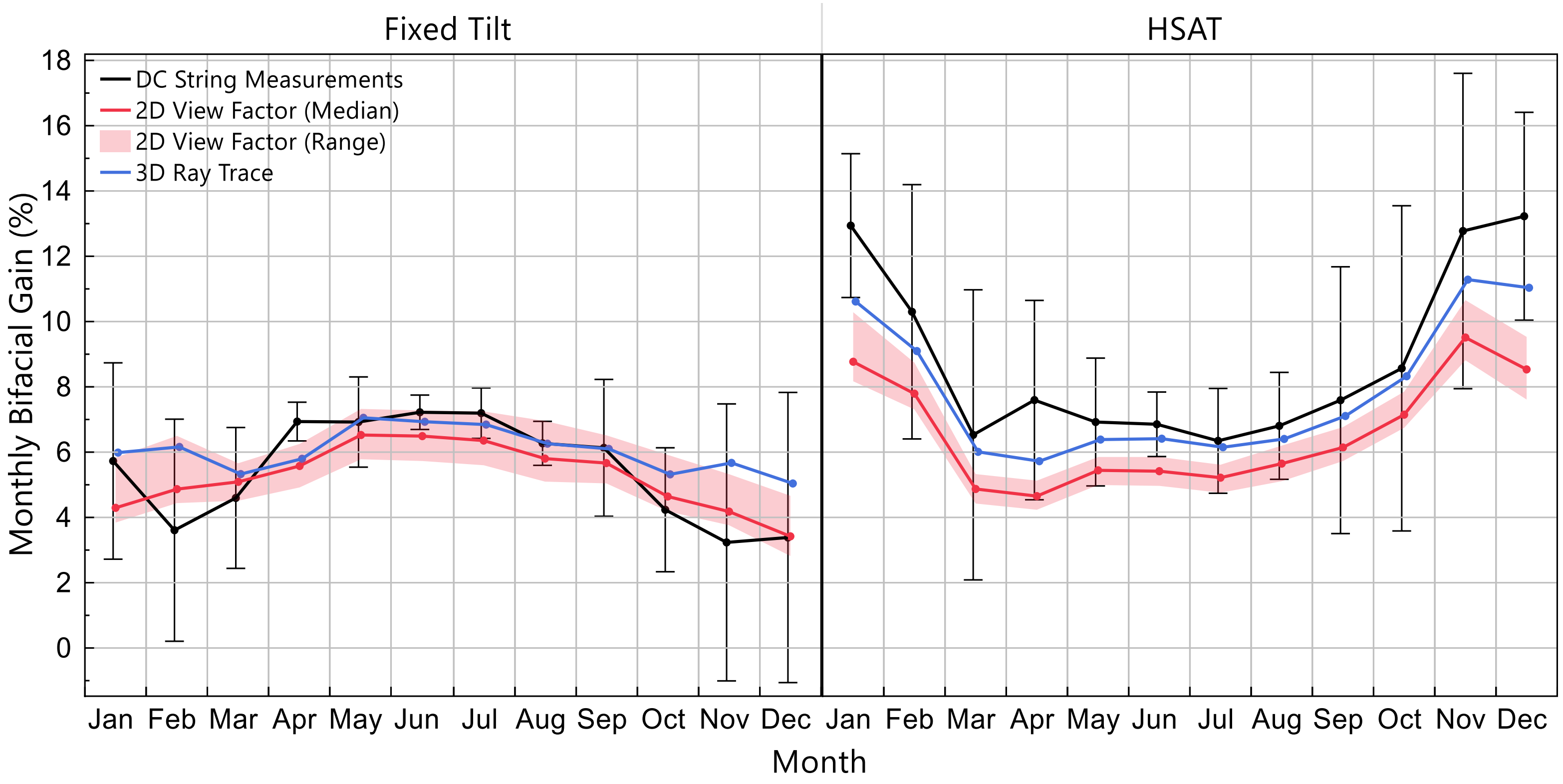
Simulated Optical Gains vs. Measured Electrical Gains

Ray tracing is closest to measurements on fixed tilt, most months

Ray tracing is always closest to measurements on the HSAT

The bifacial-specific structural losses change with conditions [1-3]

- Static value used here
- Offers room for improvement



[1] C. Deline et al., Estimating and parameterizing mismatch power loss in bifacial photovoltaic systems, *PiP, 2020*
[2] K. McIntosh et al., Mismatch Loss in Bifacial Modules Due to Nonuniform Illumination in 1-D Tracking Systems, *IEEE JPV, 2019*
[3] N. Riedel-Lyngskær et al., A Spatial Irradiance Map Measured on the Back of a Horizontal Single-Axis Tracker, *PVSC*, 2020

Summary

- Results show that state-of-the-art bifacial performance models add ~**0.5% uncertainty** to the PV modeling chain.
- Simulated rear G_{POA} values match better to measurements made on fixed tilt than to measurements on tracking systems, at this site.
- 2DVF fixed tilt simulations are mostly w/in ±1% of measured monthly bifacial gain.
  - 2DVF HSAT simulations w/in ~2%, 3DRT w/in ~1%.
- These are results from 1 site, more validation studies are needed to reduce the perceived risk of bifacial PV!

EUROPEAN ENERGY

eUDP

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

PEARL PV

For more details see:

Riedel-Lyngskær et al. *Applied Sciences*, 2020, 10, 8487

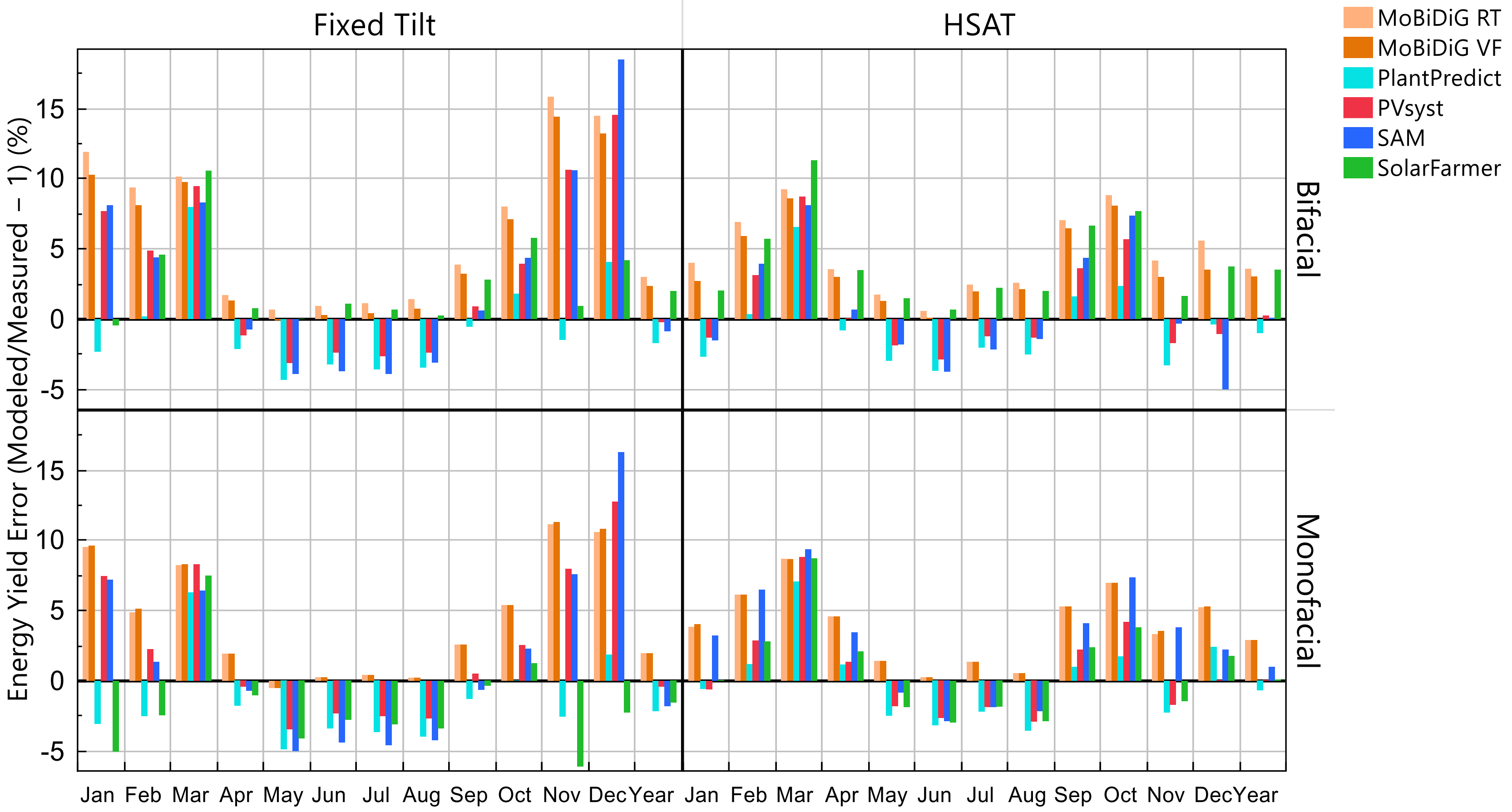
https://www.mdpi.com/2076-3417/10/23/8487

APPENDIX SLIDES

Modeled vs. Measured Energy

- The annual errors in bifacial and monofacial simulations are no more than 0.5% different when performed in MoBiDiG VF, PlantPredict, and PVsyst.

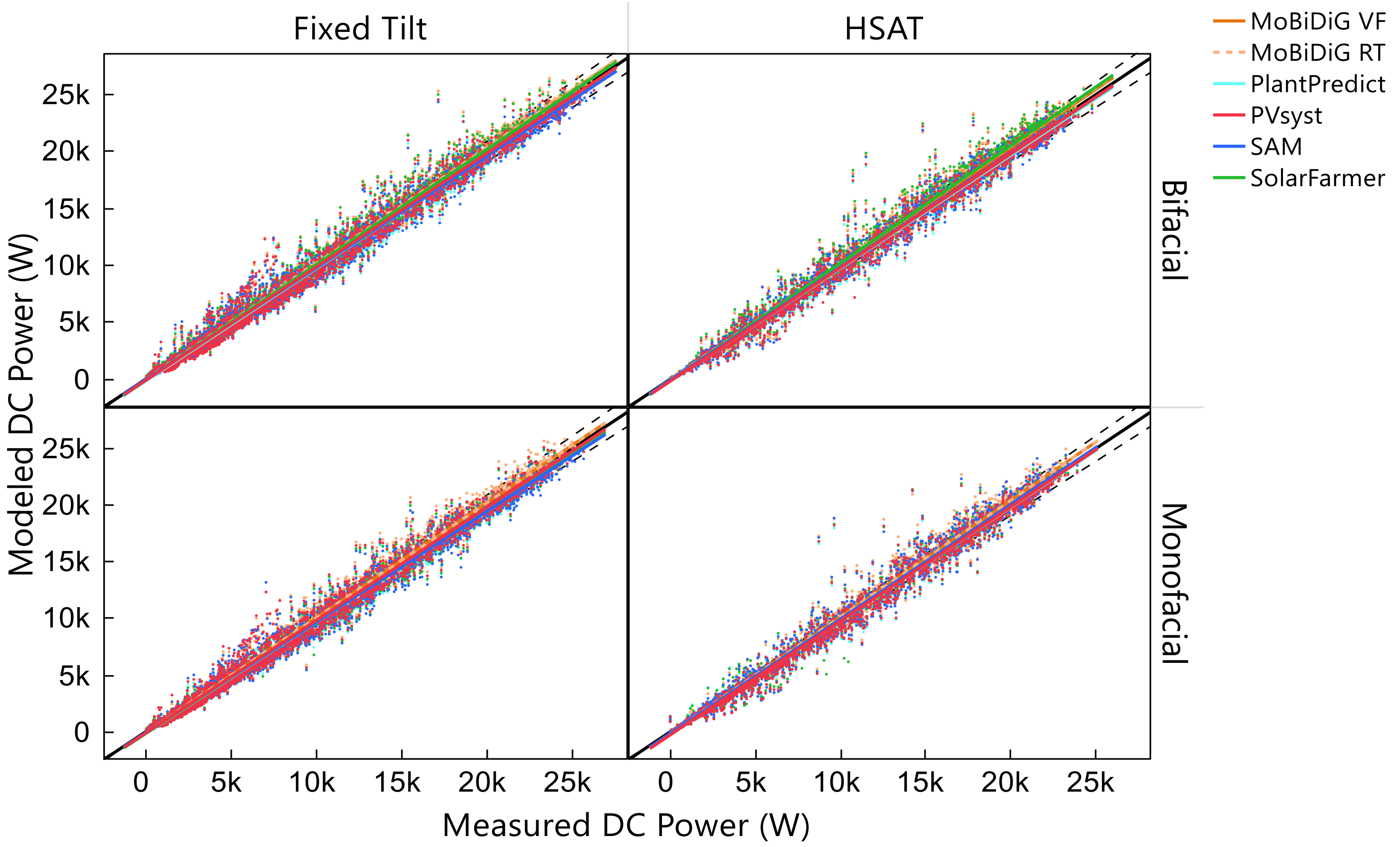
- This result is in accord with the $G_{POA,Rear}$ results: roughly 0.5% between modeled and measured values when considering the contribution of $G_{POA,Front}$.



Modeled vs. Measured DC Pmax

Mean Absolute Errors (W/m2)

Software	Bifacial Fixed Tilt	Bifacial HSAT	Monofacial Fixed Tilt	Monofacial HSAT
MoBiDiG RT	508	527	467	508
MoBiDiG VF	509	506	464	507
PlantPredict	557	548	521	497
PVsyst	567	487	521	485
SAM	568	523	553	514
SolarFarmer	486	567	492	478



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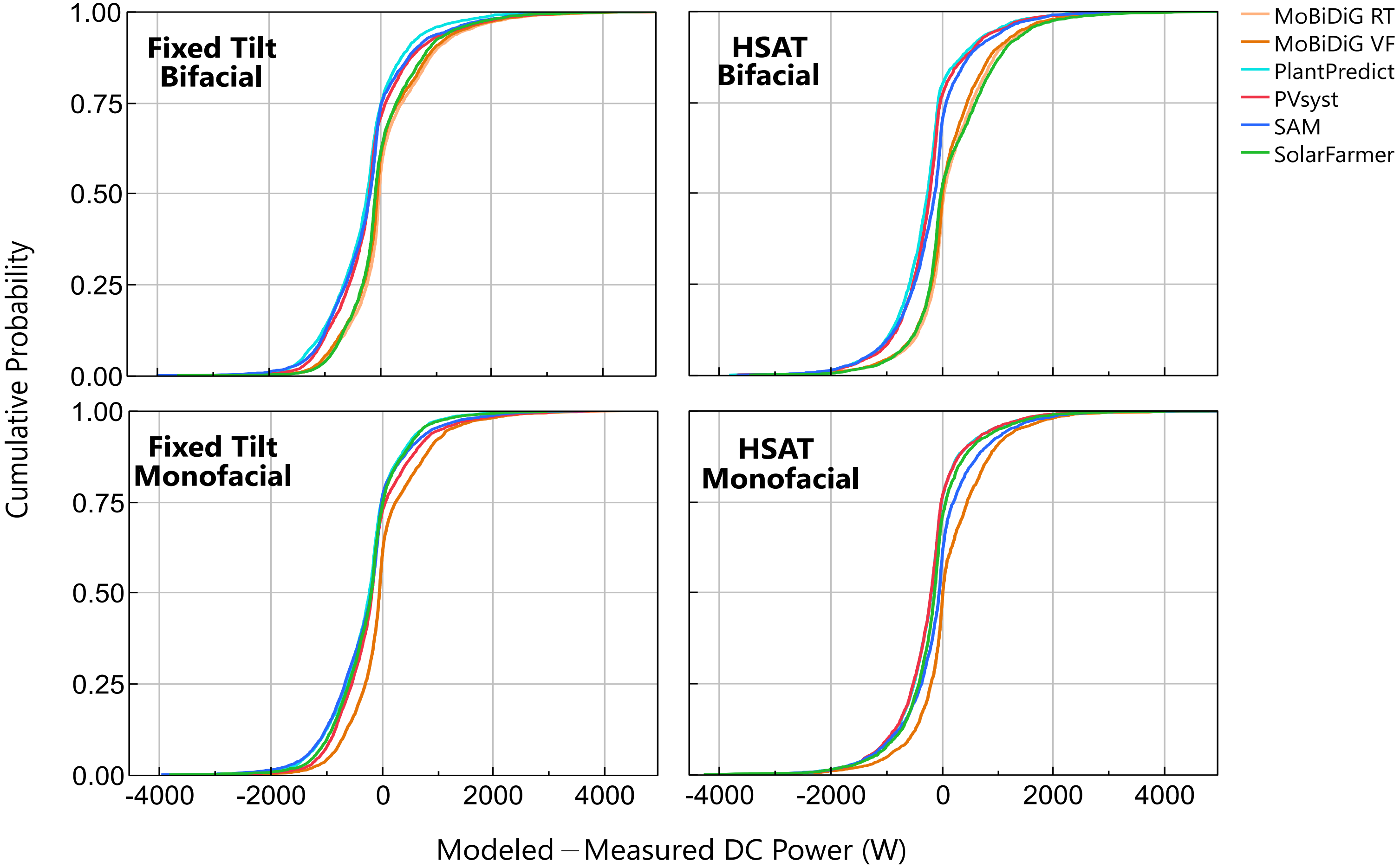
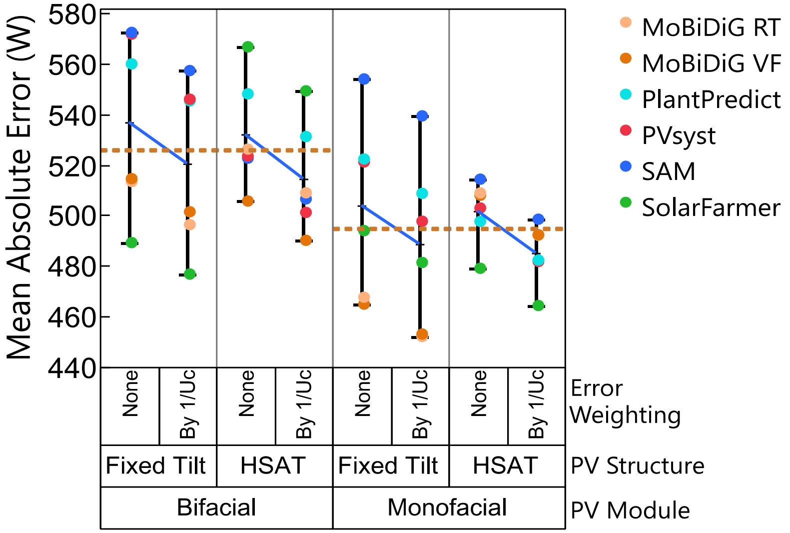
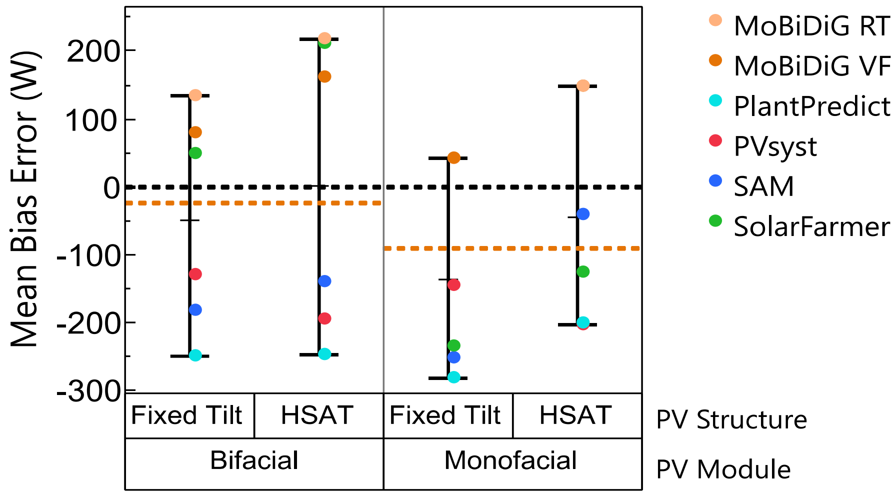
PlantPredict	557	548	521	497
PVsyst	567	487	521	485
SAM	568	523	553	514
SolarFarmer	486	567	492	478



DTU

Goodness of Fit for DC Pmax: mono v. bifacial





Variability plots showing goodness of fit summaries (MAE and MBE)

Each range bar is constructed by the results from the 6 software with an electrical model

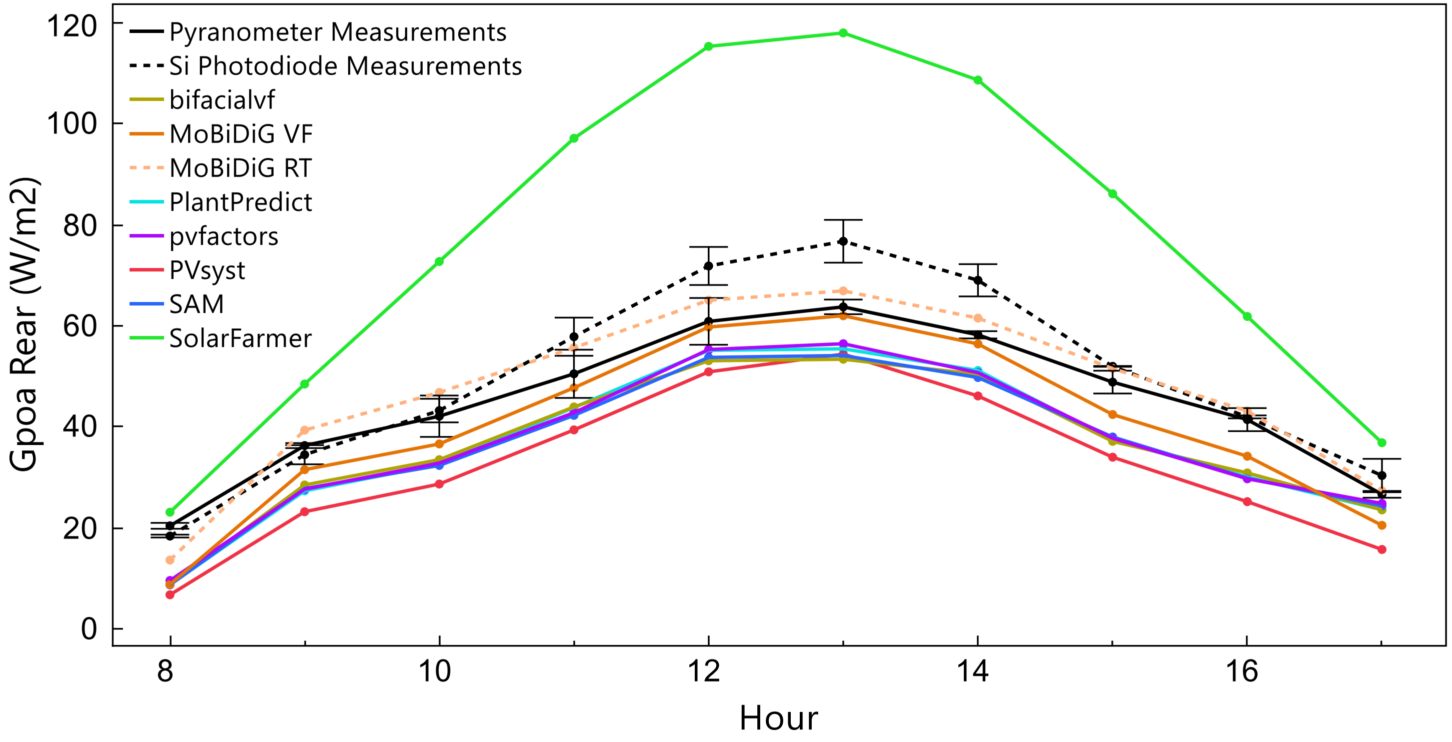
Rear POA Irradiance Timeseries Comparisons: Single Axis Tracker

Si Photodiode measurements overestimate due to red-shifted spectrum.

Error bars constructed from measurements from two sensors (E/W)

Typically, the sensor farthest from the ground receives more irradiance.

- i.e. West in AM, East in PM

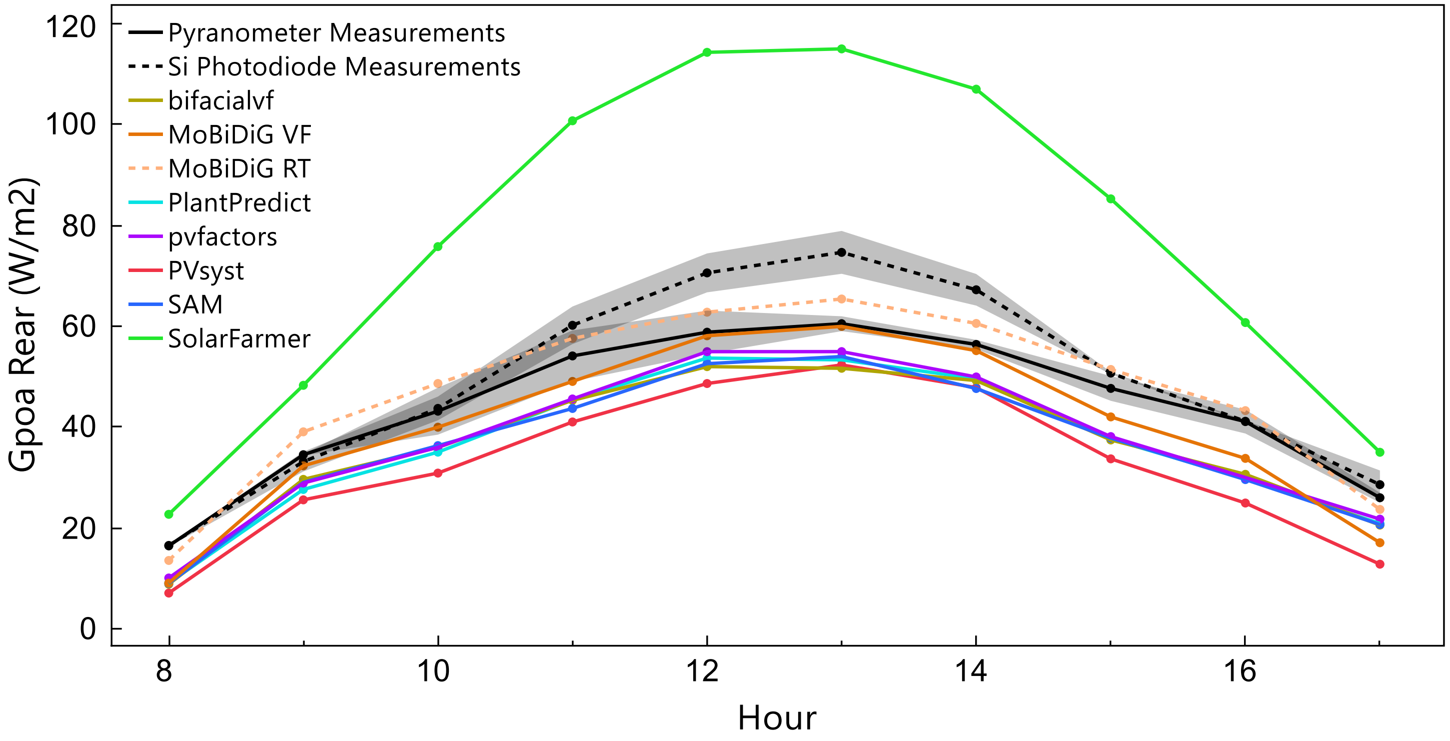


Rear POA Irradiance Timeseries Comparisons: Single Axis Tracker

The measurement range doesn't overlap most simulations during high DNI conditions.

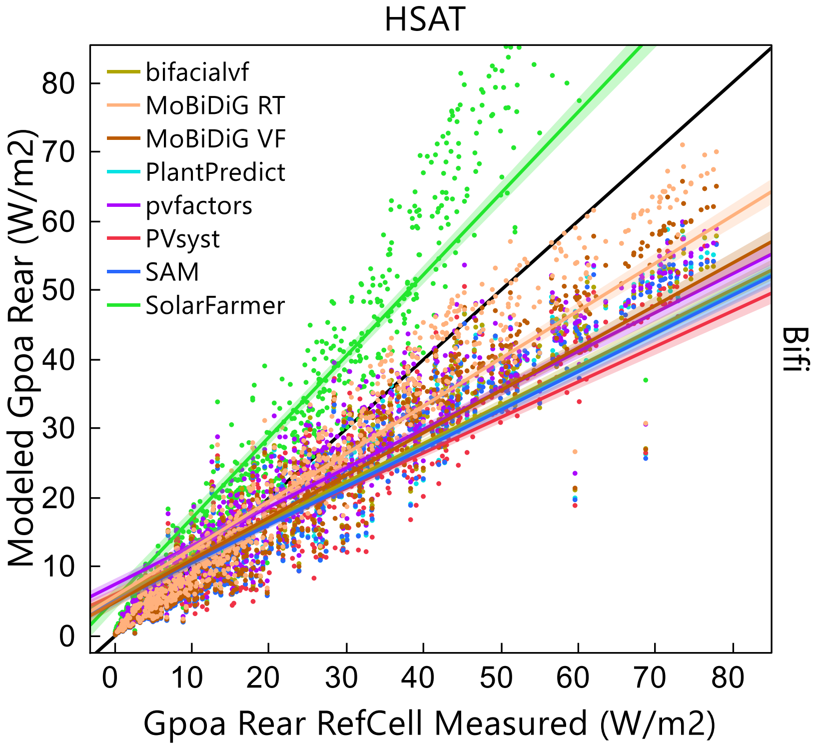
According to [1], 10^{+} modules into the array should be representative of "semi-infinite" assumption.

Tracker System (facing north)



[1] S.A. Pelaez et al., 2016. Model and Validation of Single-Axis Tracking with Bifacial PV, IEEE JPV

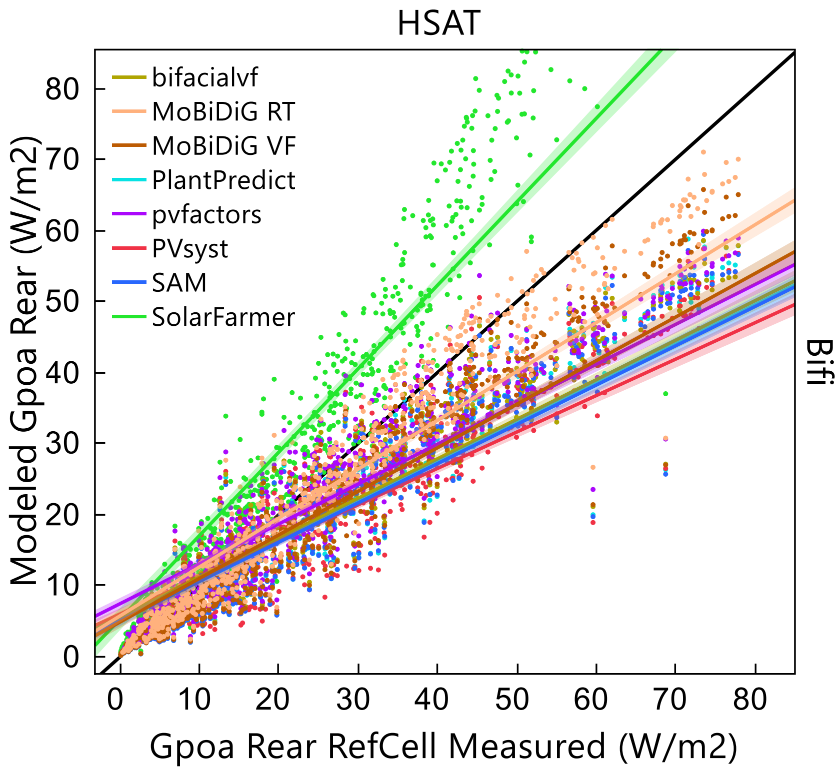
Modeled Rear POA Irradiance to Si Photodiode Measurements on Tracker System

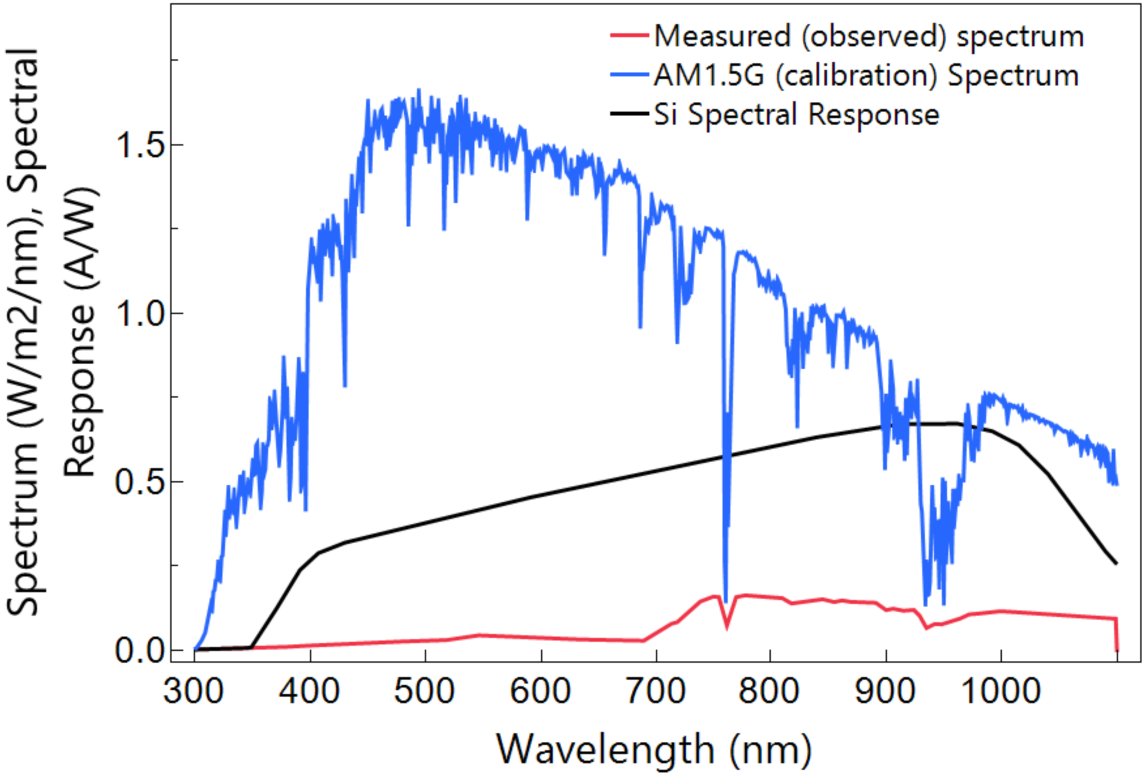


Model	MAE [W/m2]	RMSE [W/m2]
bifacialvf	5.9	13.2
MoBiDiG RT	3.5	11.4
MoBiDiG VF	5.1	12.4
PlantPredict	6.2	13.4
pvfactors	5.3	12.7
PVsyst	7.1	14.3
SAM	6.3	13.5
SolarFarmer	10.5	18.2

- Photodiode measurements are much higher than pyranometers
  - Due to high IR component in reflected spectrum
- Reference cell vs pyranometer tradeoffs/debate

Modeled Rear POA Irradiance to Si Photodiode Measurements on Tracker System





Si sensors calibrated under AM1.5G tend to have higher outputs when exposed to red-shifted spectra

Pyranometer/Pyrheliometer Uncertainty (Uc) Model

GHI Uc driven by cosine response

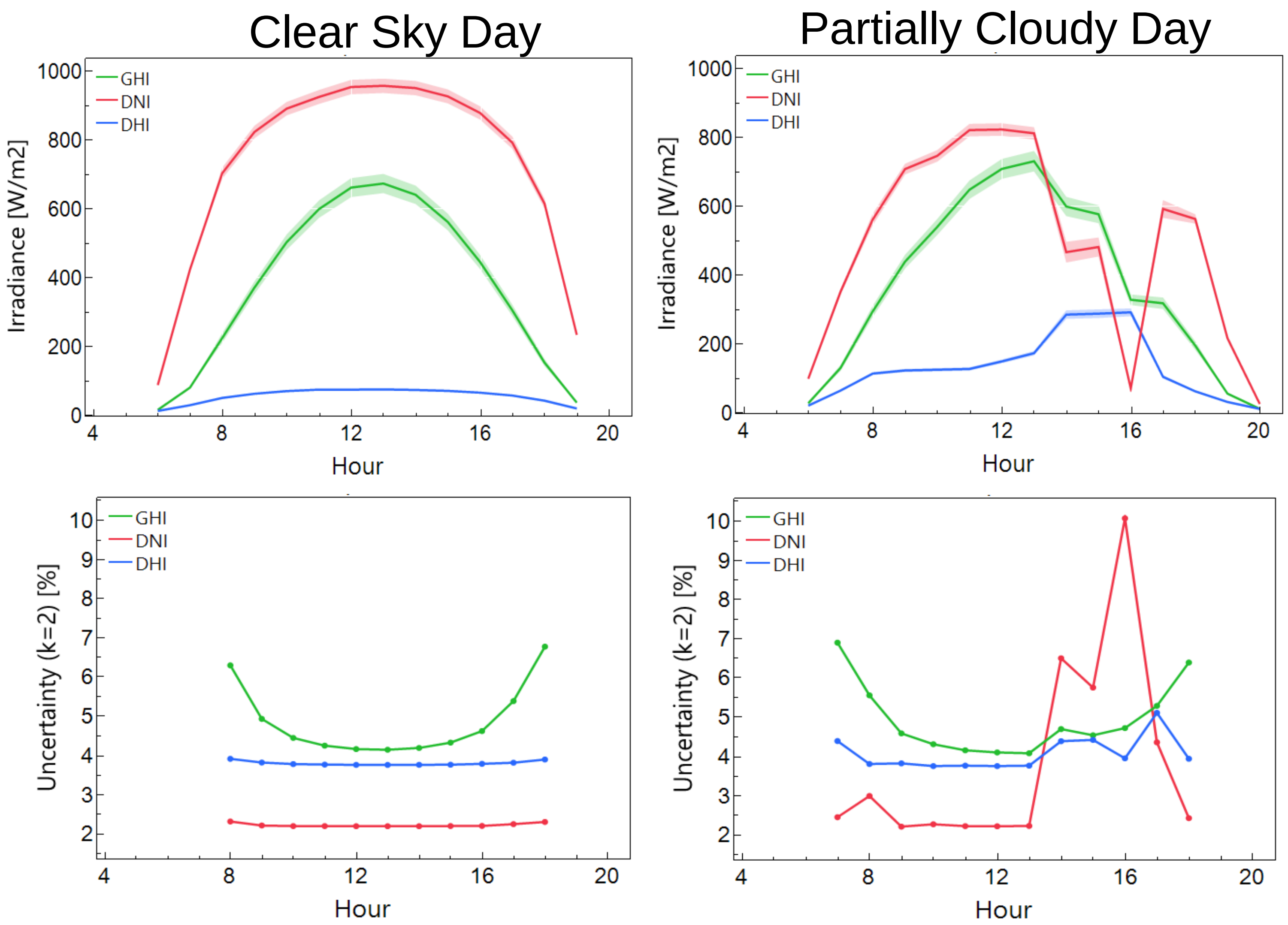
- Low sun elevation = higher uncertainty

DNI Uc affected by variability w/in hour

- According to standard error of mean (10sec sampling)

Other important Uc contributions

- Calibration Uc
- Data logger resolution
- Thermal offset
- Long term stability



Bifacial Performance Model Validation: Inputs

Electrical Parameters Used

Parameter	Monofi	Bifi	Unit	Electrical Model
ISCSTC	9.745	9.642	A	5/6 Param. DeSoto
I0	0.0065	0.0047	nA	5/6 Param. DeSoto
RS	0.304	0.382	Ω	5/6 Param. DeSoto
RSH	353.9	1891.2	Ω	5/6 Param. DeSoto
a	1.533	1.518		5/6 Param. DeSoto
Adjust	9.010	6.311		6 Param. DeSoto
ISCSTC	9.690	9.640	A	PVsyst
I0	4.077	3771	nA	PVsyst
RS	0.181	0.010	Ω	PVsyst
RSH	300	4997	Ω	PVsyst
RSH,0	1200	1500	Ω	PVsyst
Gamma	1.190	1.740		PVsyst

Bifi-Specific Parameters Used

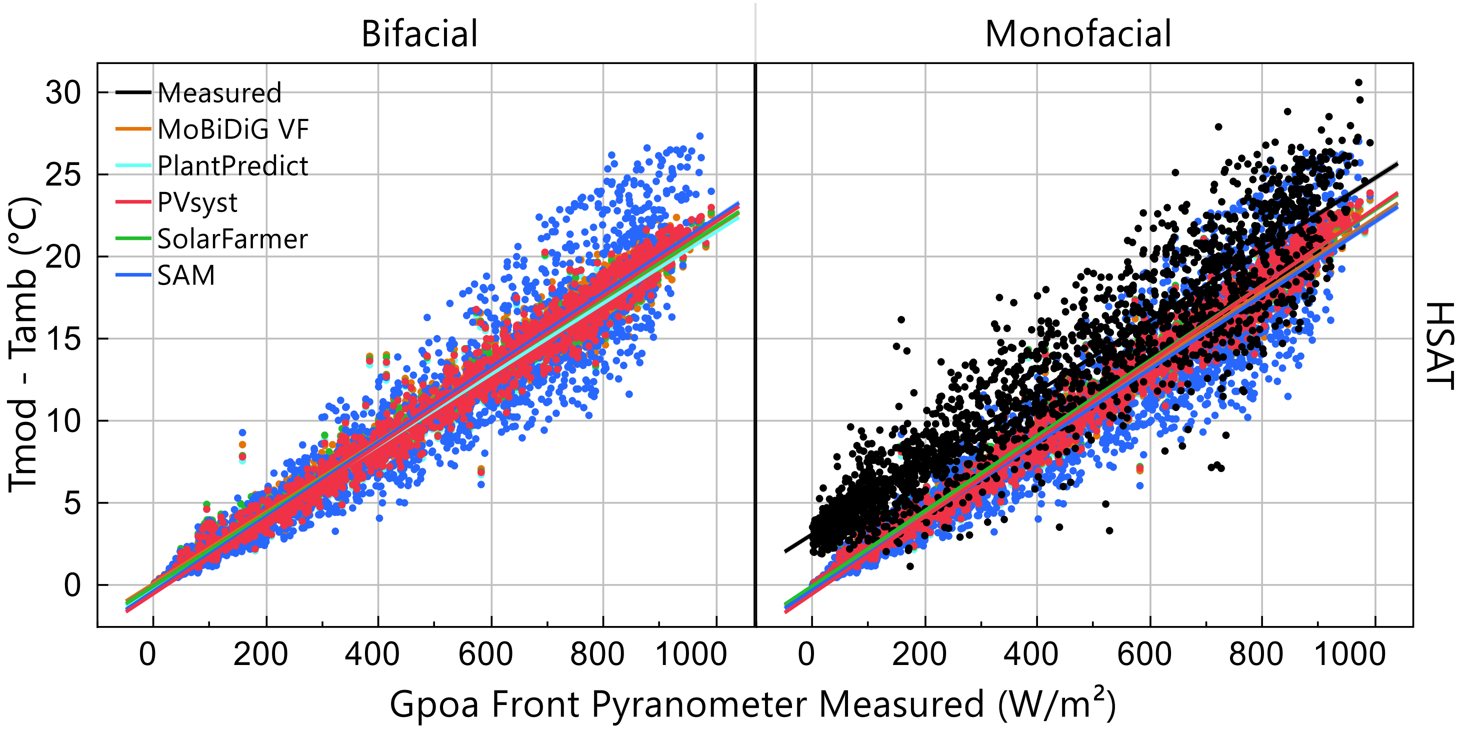
Parameter	Value [%]
Bifaciality	67.0
Transmission fraction	3.75
Mismatch loss factor	2.50
Structure shading factor	0.70
Front PV surface reflectivity	1.00
Rear PV surface reflectivity	3.00

Thermal Parameters Used

Parameter	Monofacial	Bifacial	Unit	Model
U0	29.5	31	Wm-2K	Faiman
U1	1.6	1.6	Wm-3Ks-1	Faiman
NOCT	42	42	C	NOCT
NOCT Adjust	0	0	C	NOCT

Bifacial mismatch determined from: N. Riedel-Lyngskær et al., A Spatial Irradiance Map Measured on the Back of a Horizontal Single-Axis Tracker, PVSC 2020

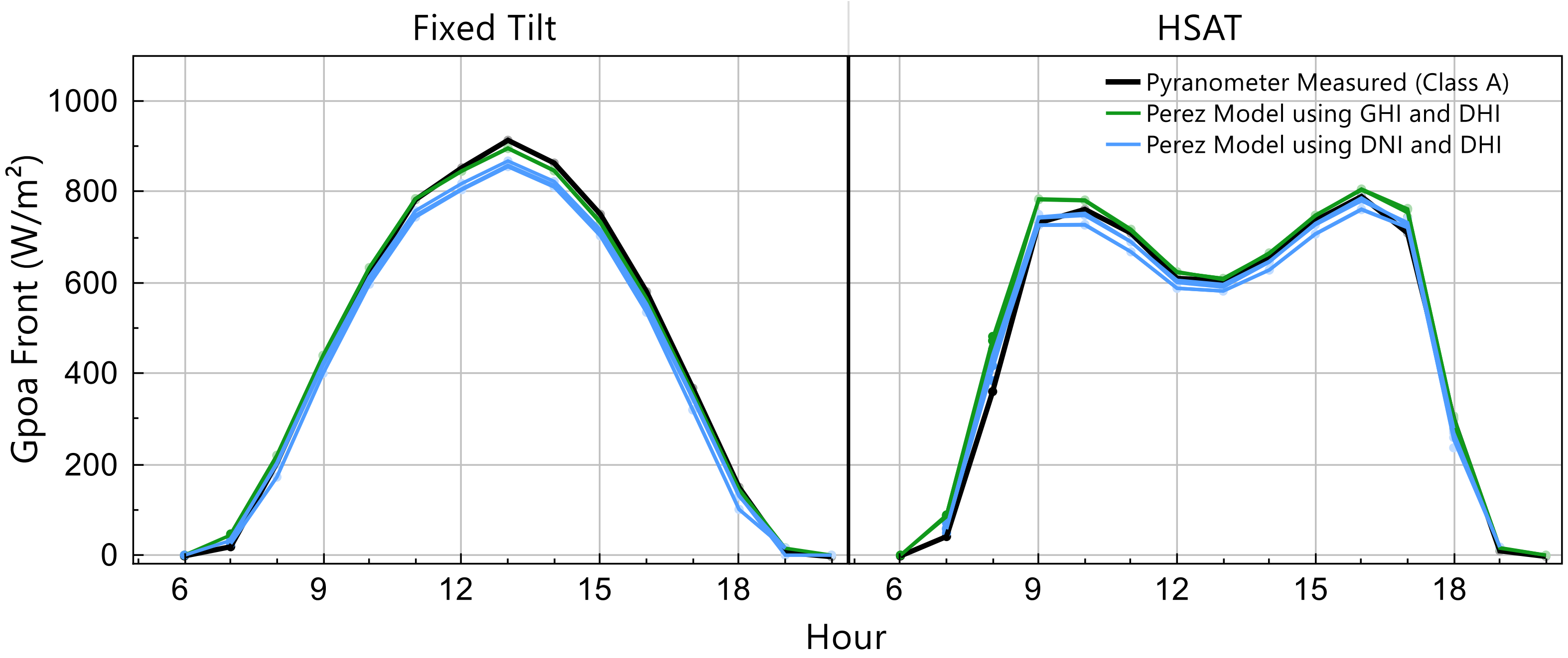
Thermal performance



Single RTD placed on the back of one cell in the array.

Sensitivity analysis of the U_0 and U_1 coefficients suggested that the cell which we measured was not representative of the array temperature.

Frontside Gpoa: Modeled vs. Measured



All software use Perez model, but they don’t give the same result when given the same meteo file:

- Use of GHI vs DNI
- Sun position calculation
- Tracker position calculation

Low Light Efficiency: Model Differences

Greatest differences occur at low light.

SAM and MoBiDiG use DeSoto Model

PP, PVsyst, and SF use PVsyst 1-diode model

Optimized param set for low light performance offers room for improvement

Average modeled cell temperature used for correction to 25C.