Comparison of Open-Source Photovoltaic Performance Models Against Multi-Year Field Data

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Motivation

- Models vary widely according to the inputs they take and the complexity of their calculations
- Comparisons of models exist, but are usually limited
- PVPMC blind modeling comparison highlighted errors caused by modeler skill and varied assumptions

Aimed to :

- **Create a comprehensive comparison of all open-source models against multi-year data from different c-Si technologies**
- **Remove modeler skill and varied assumptions from the analysis**

SLTE Systems

SLTE systems located at Sandia National Laboratories

System information of the seven SLTE systems used in the study

Manufacturer & Model	Cell Technology	# of Modules	Installation Date	Start Date*	Abbreviation Used
LG 320N1K-A5	N-PERT Si	4 strings of 12 (48)	June 2018	May 2018	LG320
Panasonic VBHN325SA16	HIT Mono Si	4 strings of 12 (48)	June 2018	May 2018	Panasonic325
Canadian Solar CS6K-270P	Poly-Si	4 strings of 12 (48)	October 2017	January 2018	CSpoly270
Canadian Solar CS6K-275M	Mono-Si	4 strings of 12 (48)	October 2017	January 2018	CSmono275
Hanwha Q Cells Plus Q.Plus BFR-G4.1 280	Poly-Si PERC	4 strings of 12 (48)	October 2017	January 2018	Qpoly280
Hanwha Q Cells Peak Q.Peak BFR-G4.1 300	Mono-Si PERC	4 strings of 12 (48)	October 2017	January 2018	Qmono300
Mission Solar MSE300SQ5T	Mono-Si PERC	4 strings of 12 (48)	May 2019	May 2019	Mission300

*All systems' reporting periods end on the same day: December 31, 2021

Our Data

Measured Weather & System Data

- GHI, DNI, DHI
- Measured Plane-of-Array (POA)
- Wind Speed
- Ambient Temperature
- Module Temperature
- String Level Voltage & Current

1-min interval for up to 4 years

Measured Module Specific Characterization Data

IEC 61853-1 Data

Measurement of Isc, Voc, Imp, Vmp, Pmp at different combinations of irradiance (100-1100 W/m^2) and temperature (15-75 ℃)

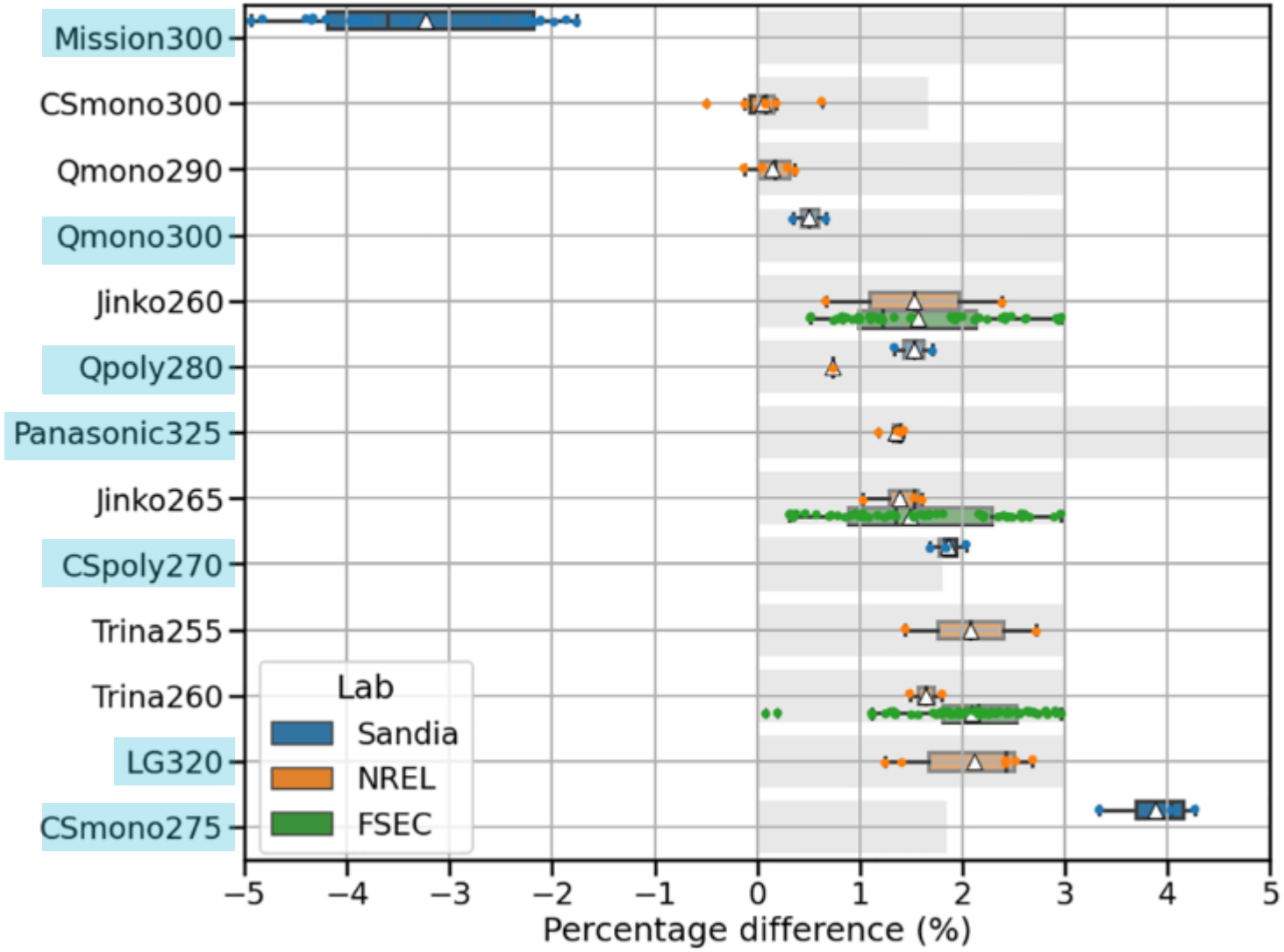
- PAN Files
- SAPM Coefficients

No spec sheet data used

Spec Sheet vs Module Specific Data

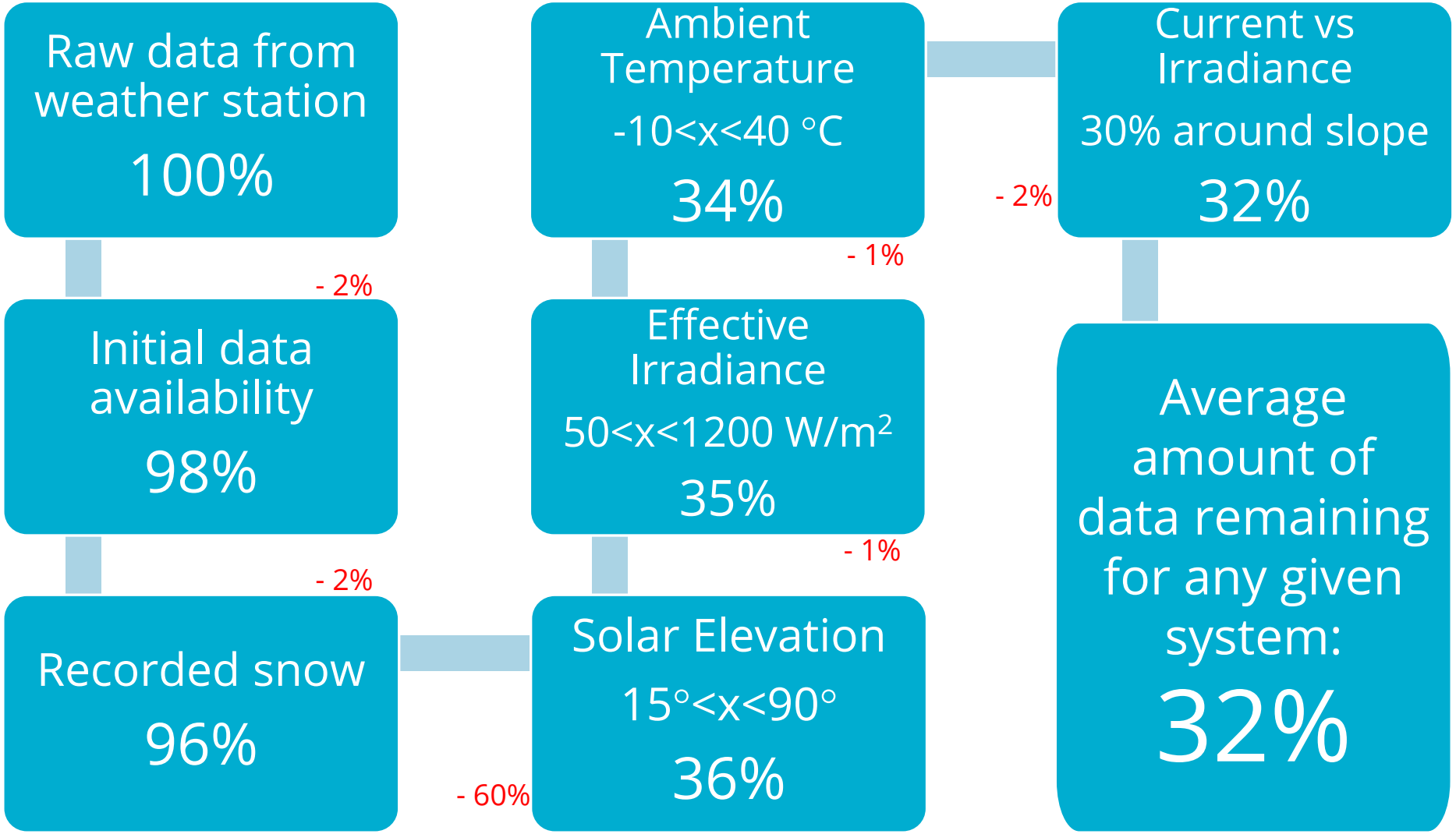
- Spec sheets are representative of a larger population of modules
- But module performance may deviate from specification sheet
- Some modules were underrated while others were over rated by as much as 5%
- Input data being accurate to the system being modeled is important

Nameplate deviation of SLTE systems located at Sandia, NREL, and FSEC



Theristis M, Stein JS, Deline C, et al. Onymous early-life performance degradation analysis of recent photovoltaic module technologies. Prog Photovolt Res Appl. 2023;31(2):149-160. doi:10.1002/pip.3615

Data Preparation



POA Transposition Models

- Isotropic
- Perez (& all submodels)
- Haydavies
- Klucher
- Reindl
- King

- All models came from *pvlib-python*
- Perez has 11 variations of coefficients
- Compared against measured POA from a pyranometer

POA Transposition Models

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Module/Cell Temperature Models

Module Temperature Models
- SAPM
- Faiman

Cell Temperature Models
- Ross
- PVSyst
- SAM NOCT
- SAPM Cell

Transient
- Prilliman
- Fuentes

- All models came from *pvlib-python*
- From T_C to T_M:

$$T_M = T_C - \frac{POA}{POA_0}\Delta T$$

- Prilliman is an additive model while Fuentes is stand-alone

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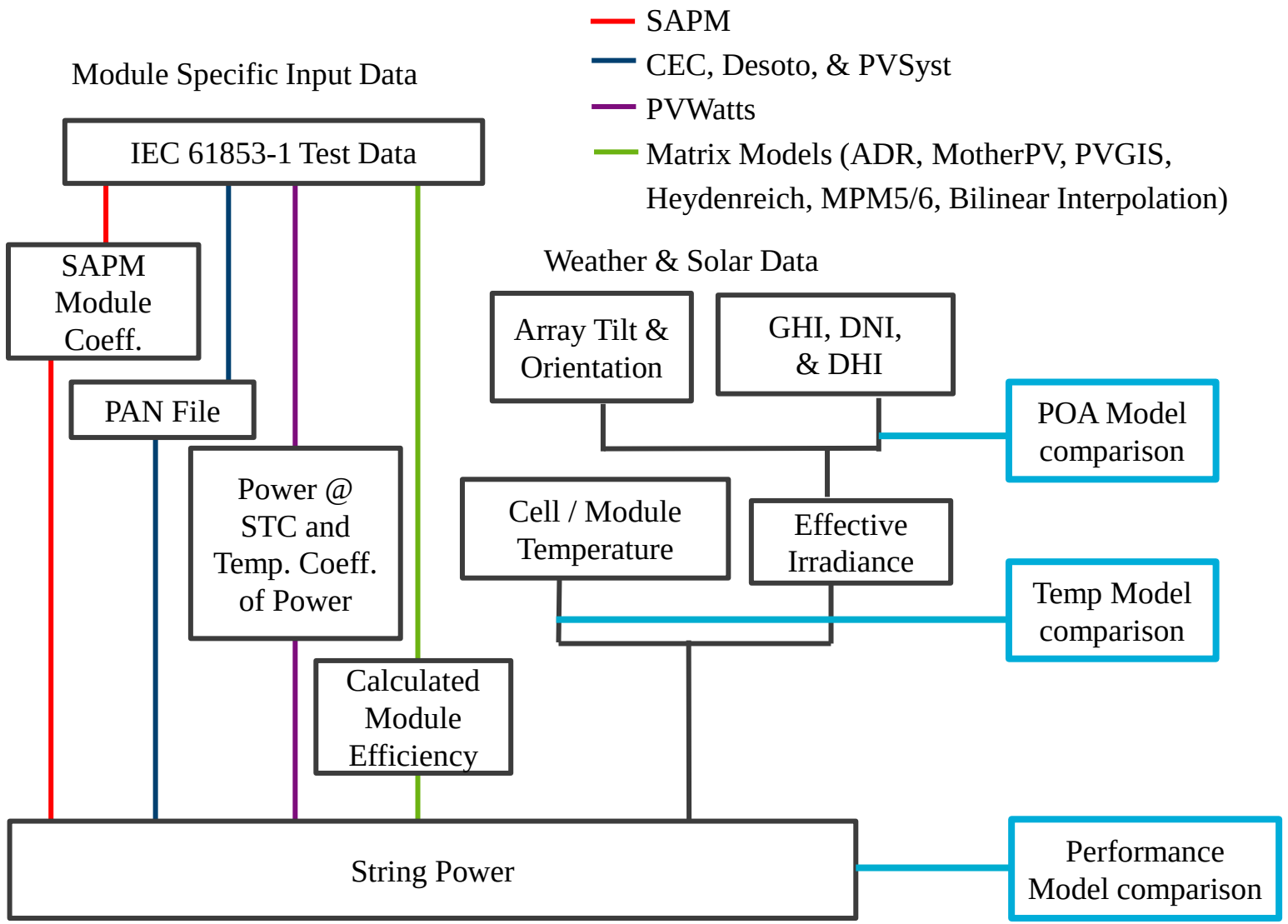
PV Performance Models

pvlib-python models
- SAPM
- PVWatts
- CEC
- Desoto
- PVSyst

pvpltools-python models
- ADR
- Heydenreich
- MotherPV
- PVGIS
- MPM5
- MPM6
- Bilinear Interpolation

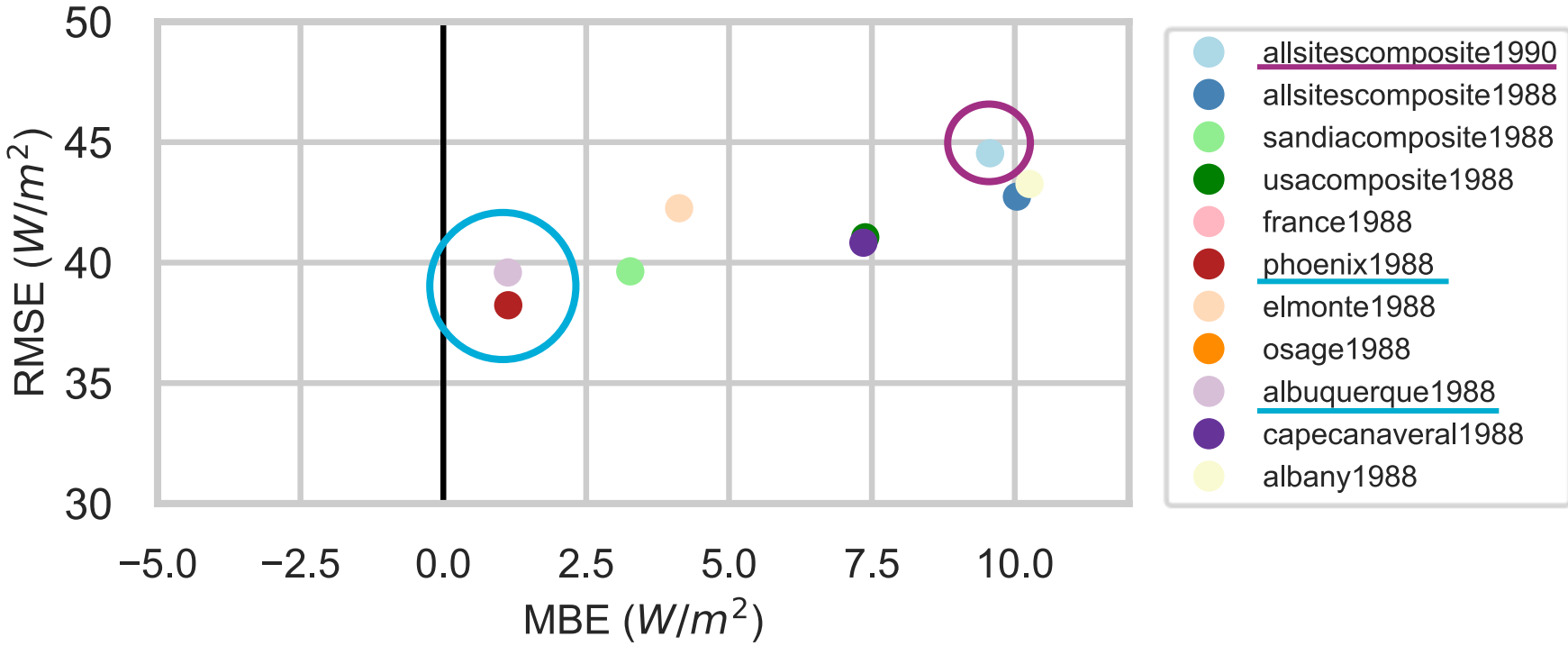
Flat 2% derate applied

Overview


SAPM
CEC, Desoto, & PVSyst
PVWatts
Matrix Models (ADR, MotherPV, PVGIS, Heydenreich, MPM5/6, Bilinear Interpolation)
Module Specific Input Data
IEC 61853-1 Test Data
SAPM Module Coeff.
PAN File
Power @ STC and Temp. Coeff. of Power
Calculated Module Efficiency
Weather & Solar Data
Array Tilt & Orientation
GHI, DNI, & DHI
POA Model comparison
Cell / Module Temperature
Effective Irradiance
Temp Model comparison
String Power
Performance Model comparison

Transposition Models - Perez

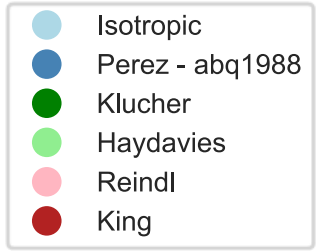
- 11 Perez models vary based on location data for the coefficients
- Best RMSE & MBE were the phoenix1988 and albuquerque1988

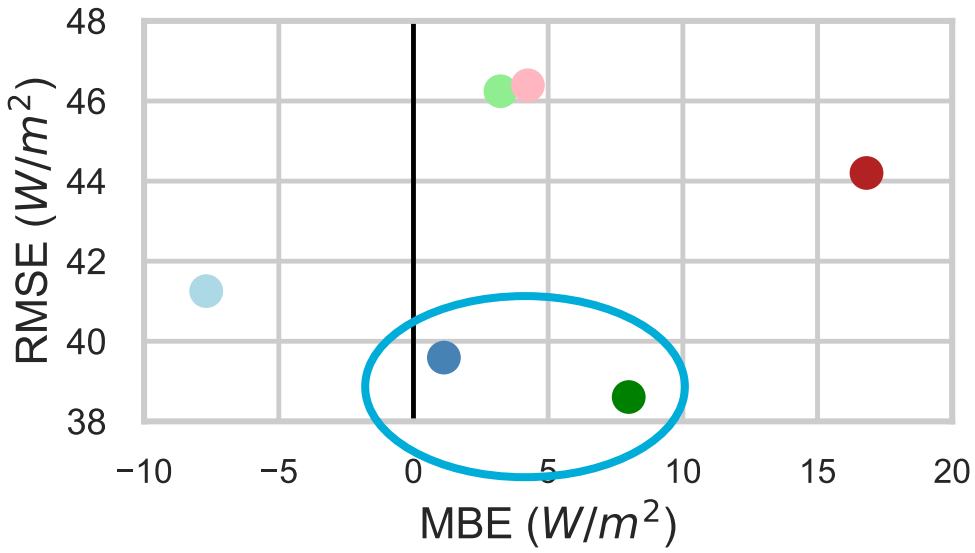


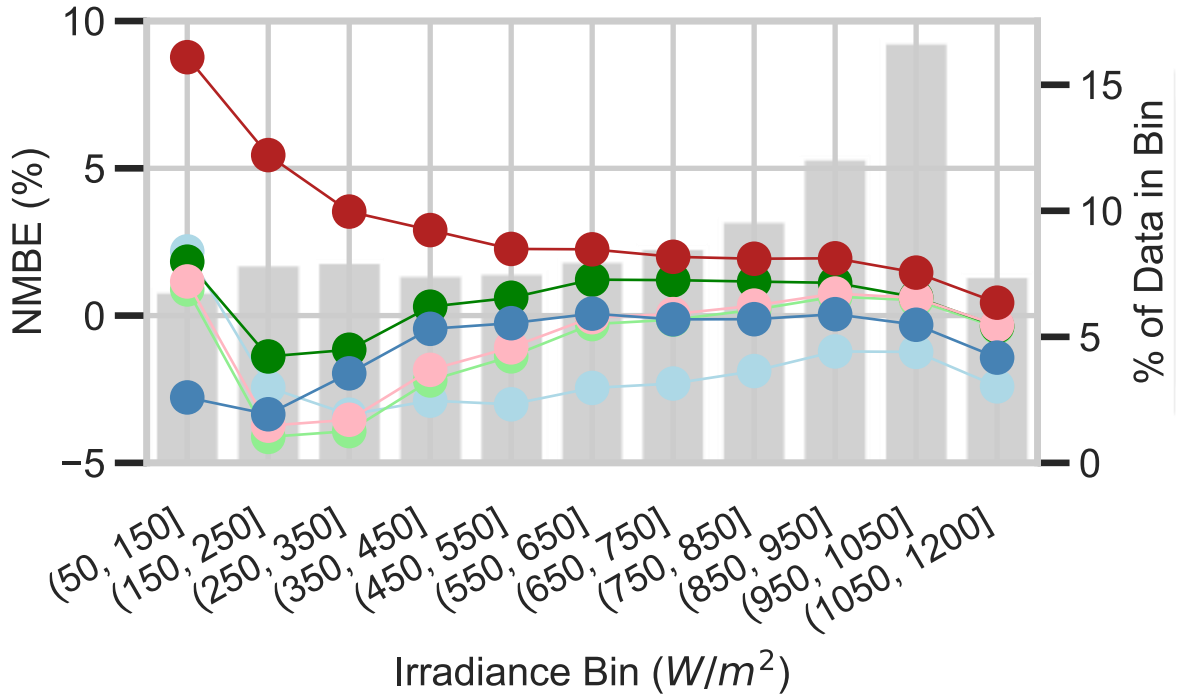
MBE vs RMSE of 11 Perez POA models

Transposition Models - All

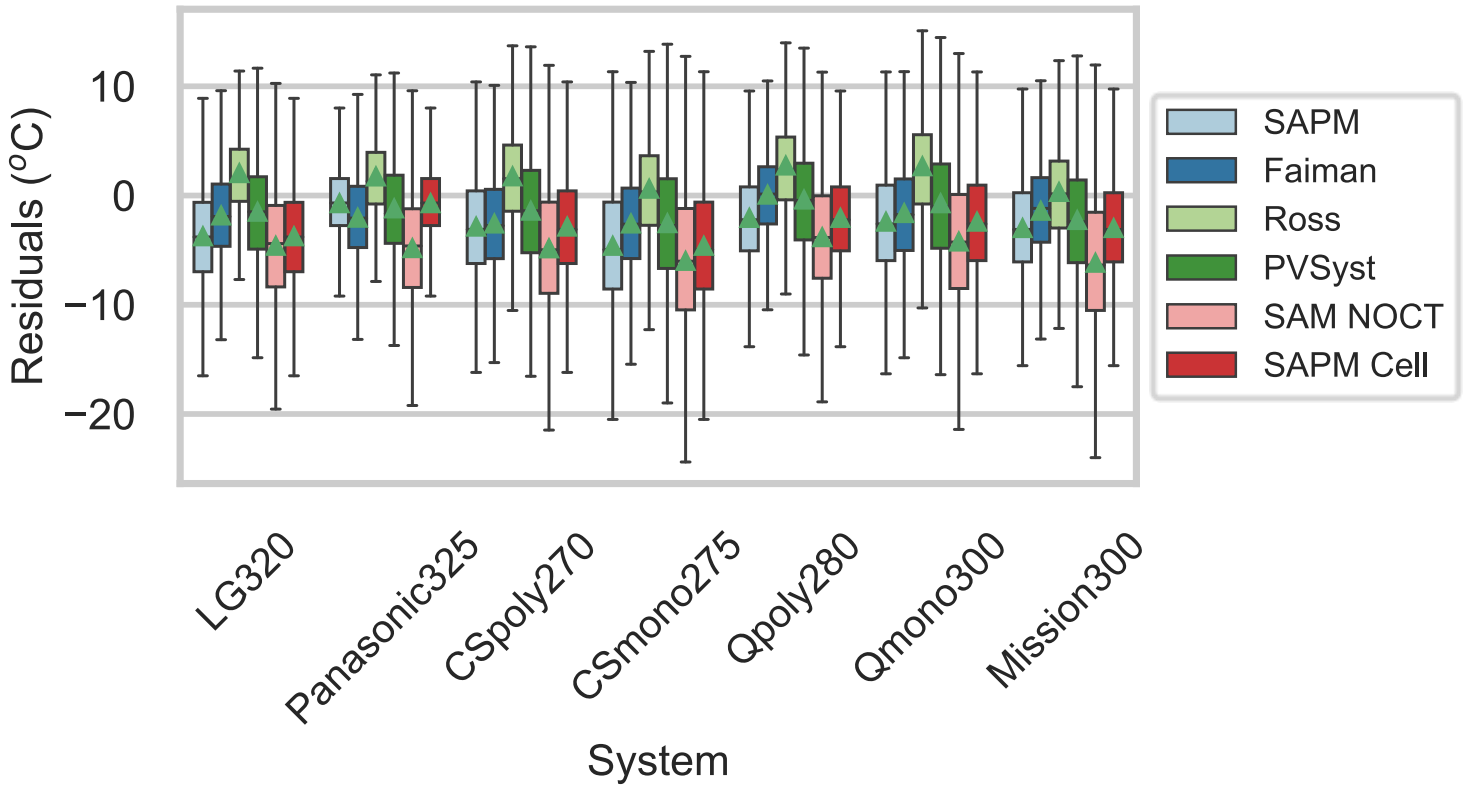
- Klucher Perez had lowest RMSE
- Overall models' NMBE was within ±3% but differences in performance can be seen at different irradiance levels
- Perez – abq1988 had most consistent performance at all irradiance levels and lowest NMBE at irradiance intervals with highest proportion of data in them







Module/Cell Temperature Models

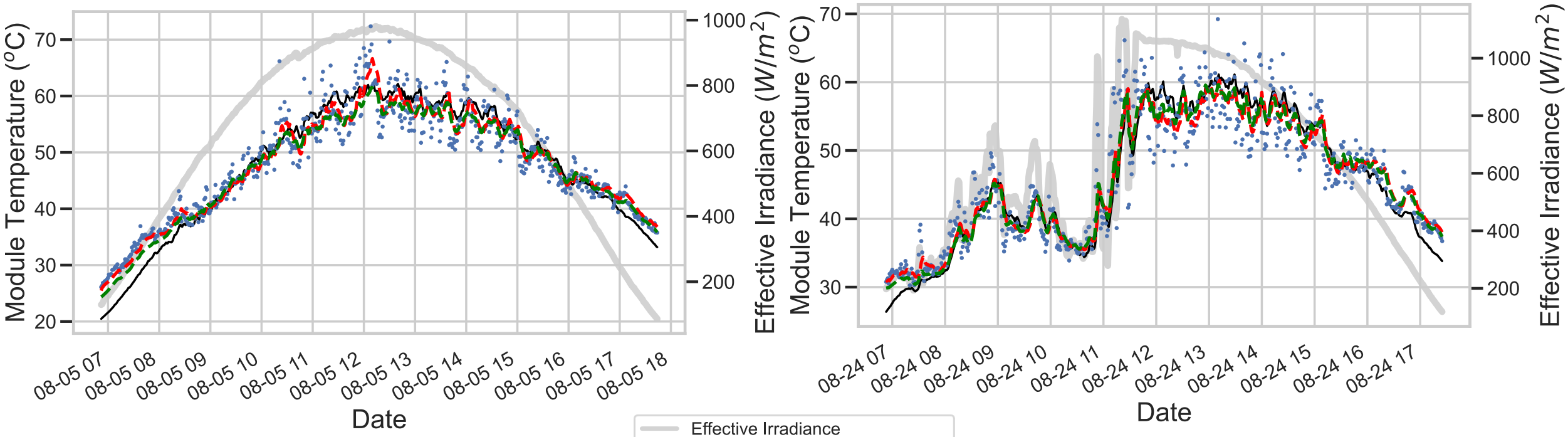


Residuals (Modeled Temperature – Measured Temperature) of module and cell temperature models

- Mean and median residuals were ± 6.5 ℃ of measured temperature
- PVSyst performed best when using a calculated efficiency based on system performance and weather conditions rather than using rated efficiency
- All models underestimated except Ross

Transient Temperature Modeling

- Additive transient Prilliman model did slightly improve all models RMSE
- Largest difference in performance can be seen when comparing sunny and cloudy days



(a) Clear sky day in August

RMSE steady-state (Faiman) – 3.6 ℃

RMSE Prilliman – 2.4 ℃

RMSE Fuentes – 2.0 ℃

(b) Cloudy day in August

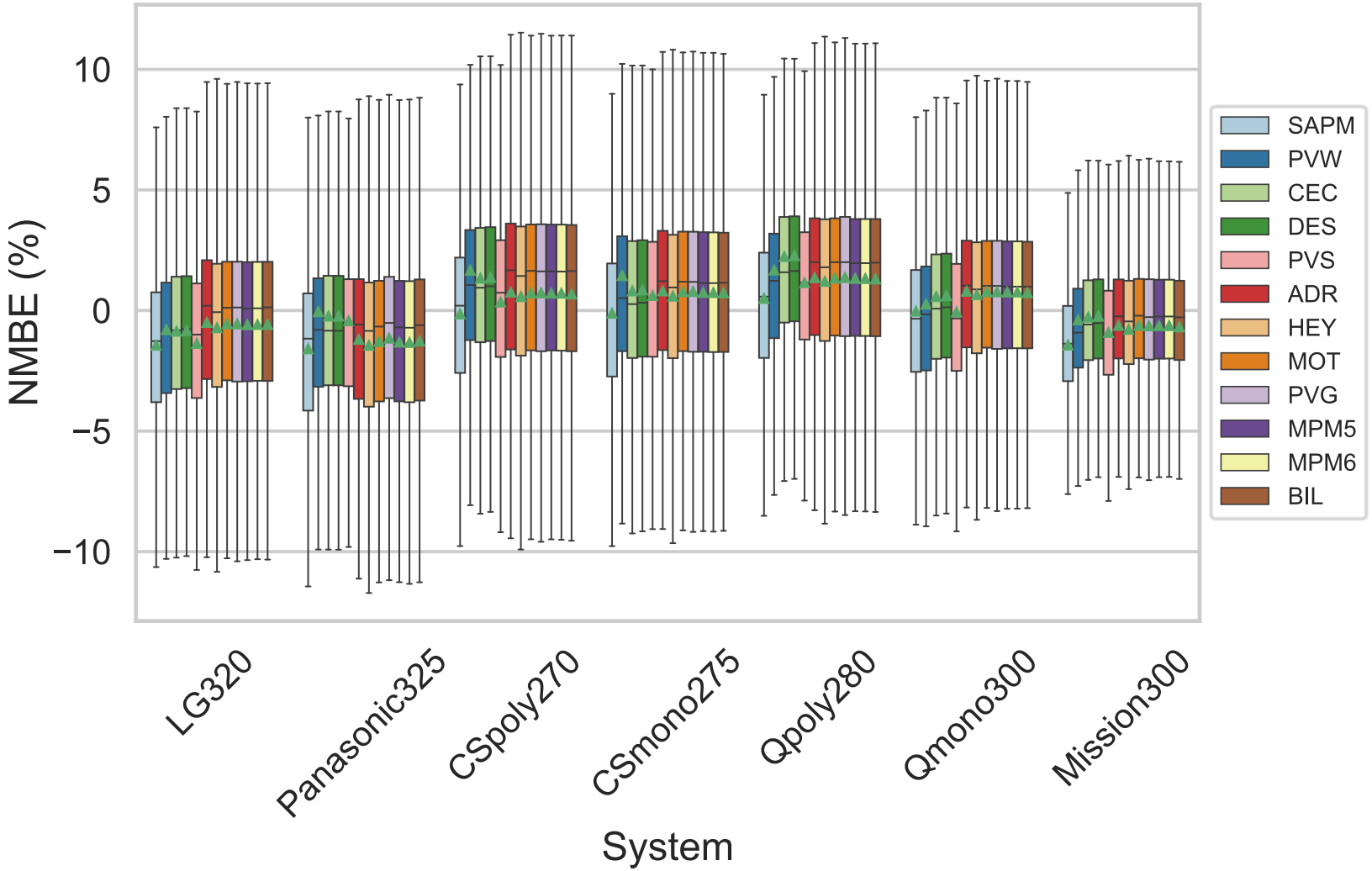
RMSE steady-state (Faiman) – 3.8 ℃

RMSE Prilliman – 2.0 ℃

RMSE Fuentes – 1.6 ℃

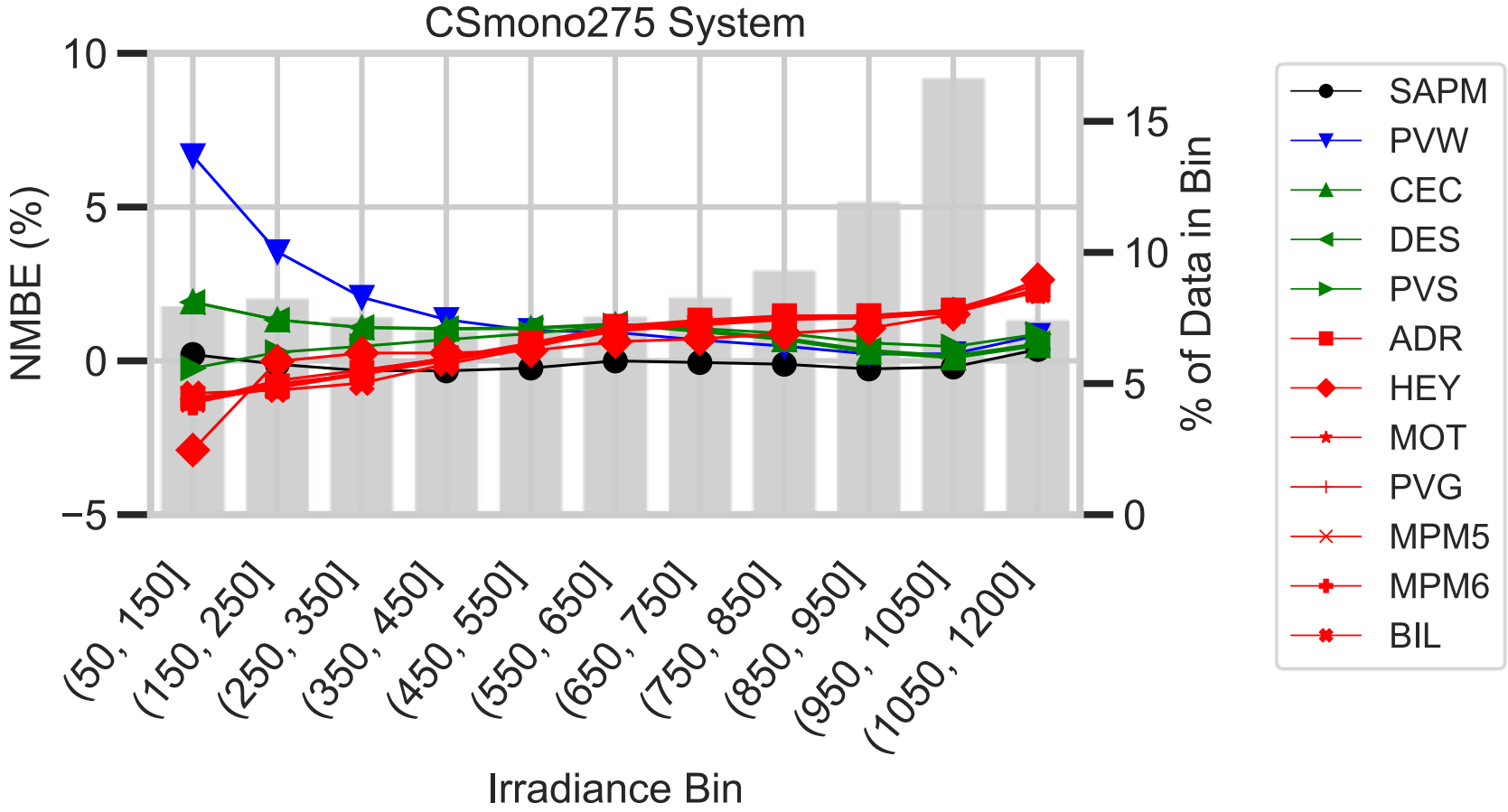
Performance Models

- 1st and 3rd quartile NMBE within ±4.2% of measured values
- Average NMBE within ±2.3% of measured values
- Simplest model performed similarly to other much more complex models



NMBE for all performance models for all systems using all years of data

Performance Models – Levels of Irradiance

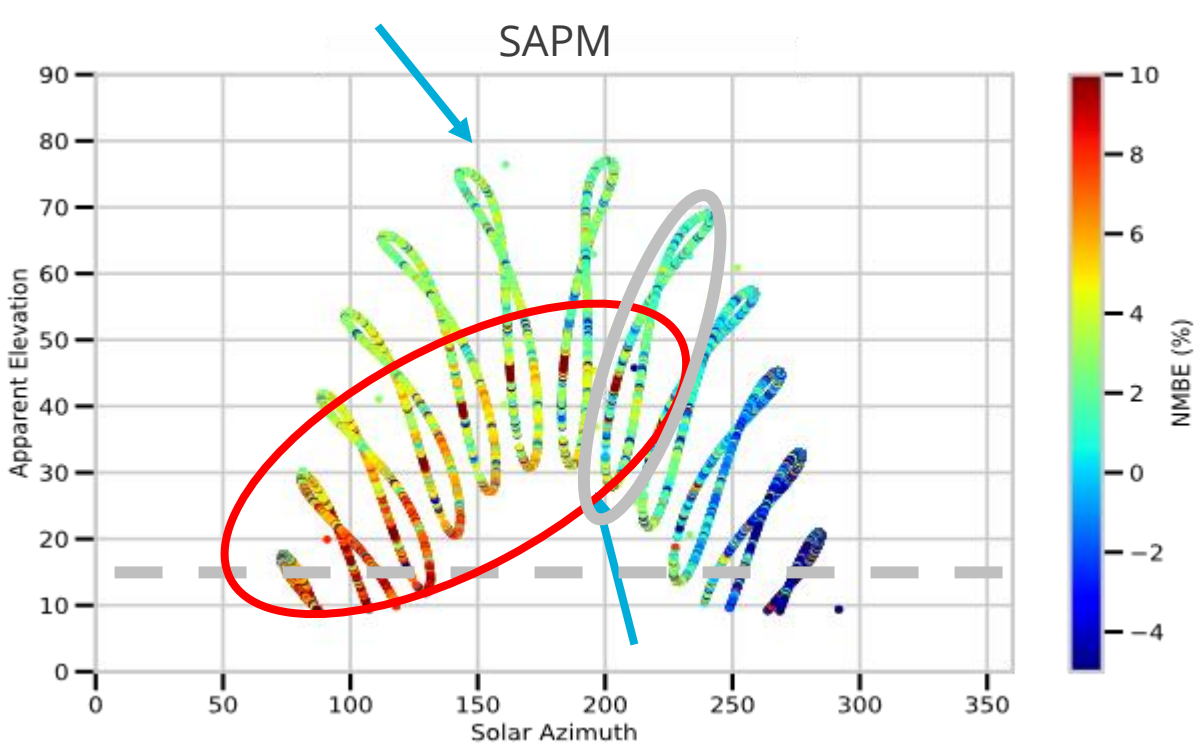


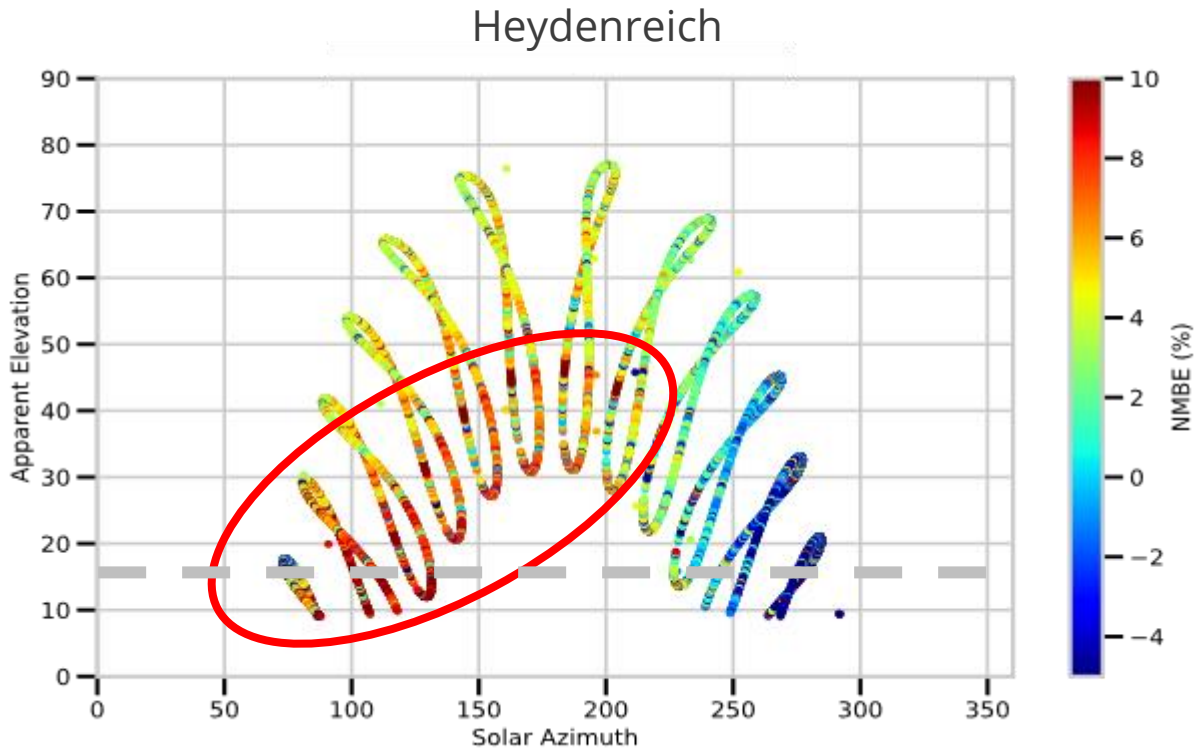
Performance models' NMBE at different levels of irradiance

- Models' performance varied at different irradiance levels
- Models were grouped by their inputs and similar models had similar performance at the different irradiance levels
- *pvlib-python* implements PVWatts v5 which removed the low-light (< 150 W/m^2) term of the equation that was present in previous versions

Performance Models – Time of Year/Day

- Models' performance varied at times of day and times of the year
- Analemma diagrams show lower NMBE in morning and later half of the year for the SAPM model than the Heydenreich model for the LG320 system





Conclusions & Future Work

- POA models performed similarly; using a location specific Perez model did improve the model's accuracy
- Temperature models' RMSE improved up to 2.2 ℃ with transient assumptions on cloudy days; these models are even more important for locations with dynamic conditions
- The performance models exhibited NMBE within ±2.3% but differences can be seen at varying levels of irradiance, times of day, and times of year
- Model complexity does not guarantee any greater accuracy
- Input module data could be more significant than the model
- This analysis allowed for an apples-to-apples comparison, whereas in our blind modeling comparison efforts the outcomes were dominated by modeler skill and derate assumptions
- Future work will include the creation of validation test protocols to reduce modeling errors and create a pathway towards standardized model validation

PVPerformance MODELING COLLABORATIVE

Please join the PVPMC at https://pvpmc.sandia.gov/ Contribute, and help increase confidence in PV system performance

Thank you!

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