Optimised fitting of indoor (e.g. IEC 61853 matrix) and outdoor PV measurements for diagnostics and energy yield predictions

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7MoO.5.4 PVSEC-27 Shiga Japan 13th Nov 2017

Present status of this study …

- A comparison of 12 existing Empirical models showed a limitation in their accuracies fitting measured data (i.e. with scatter) due to some coefficients being unphysical [1,2,3]

- Therefore an optimised Mechanistic Performance Model (MPM) was proposed with only physical coefficients

- This study looks at yearly energy yield prediction uncertainties due to fitting data vs. added random noise

[1] 7th PVPMC Canobbio, [2]44th PVSC Washington [3]33rd PVSEC Amsterdam

How some models predict PV performance from G_I and T_{MOD}

(DC Performance Ratio $PR_{DC} = Eff_{DC.MEAS}/Eff_{STC}$ or MPR)

Optimise **fit coefficients C_N** to minimise rms error using e.g. Python, Excel

Measurements

WEATHER:
Irradiance G_I
T_{MODULE}
WindSpeed

ELECTRICAL:
$PR_{DC.MEAS}$

EMPIRICAL or MECHANISTIC MODEL:

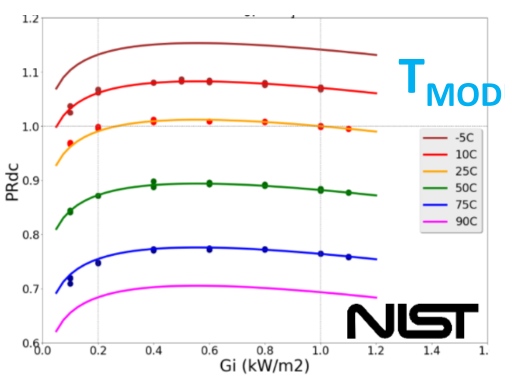
$$PR_{DC.PREDICT} = \Sigma_N C_N * func_N(G_I, T_{MOD} \dots)$$

PREDICTED PERFORMANCE:
$PR_{DC.PREDICT}$

3-7 Fit Coefficients C_N

Weather functions

PR_{DC} →



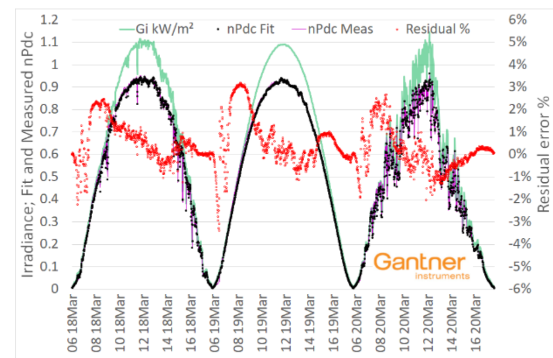
T_{MODULE}

Irradiance→

Fit indoor IEC-61853-1 matrix data
(NIST/CFV)

Fit outdoor data vs. time

nP_{DC} →



Time→

How does PV performance depend on weather inputs?

Model only expected behaviour

1. $I_{MAX} \propto G_I$ — Module STC rating actual/nominal
2. $P_{MAX} \propto (1+\gamma*(T_{MOD}-25))$ … — Power temperature coefficient "γ"
3. $V_{MAX} \propto \log(G_I)$ — From diode equation
4. $\Delta P_{MAX} \propto I_{MAX}^2 * R_{SERIES}$ — $I^2.R_S$ loss
5. $T_{MOD} \sim T_{AMB} - fn(Windspeed)$ — NMOT Thermal rise
6. $R_{SHUNT} \propto 1/\exp(G_I)$ — (dependant on PV technology)

$$PR_{DC} = C_1 + C_2*(T_{MOD}-25) + C_3*Log_{10}(G_I) + C_4*G_I + C_5*WS + \cancel{(C_6/G_I)} \text{ <MPM>}$$

$P_{MAX.ACTUAL}$ | Temperature | Voc | R_{SERIES} | NOCT | «R_{SHUNT}»

MPM model has only "Meaningful, Orthogonal, Robust, Normalised" coefficients

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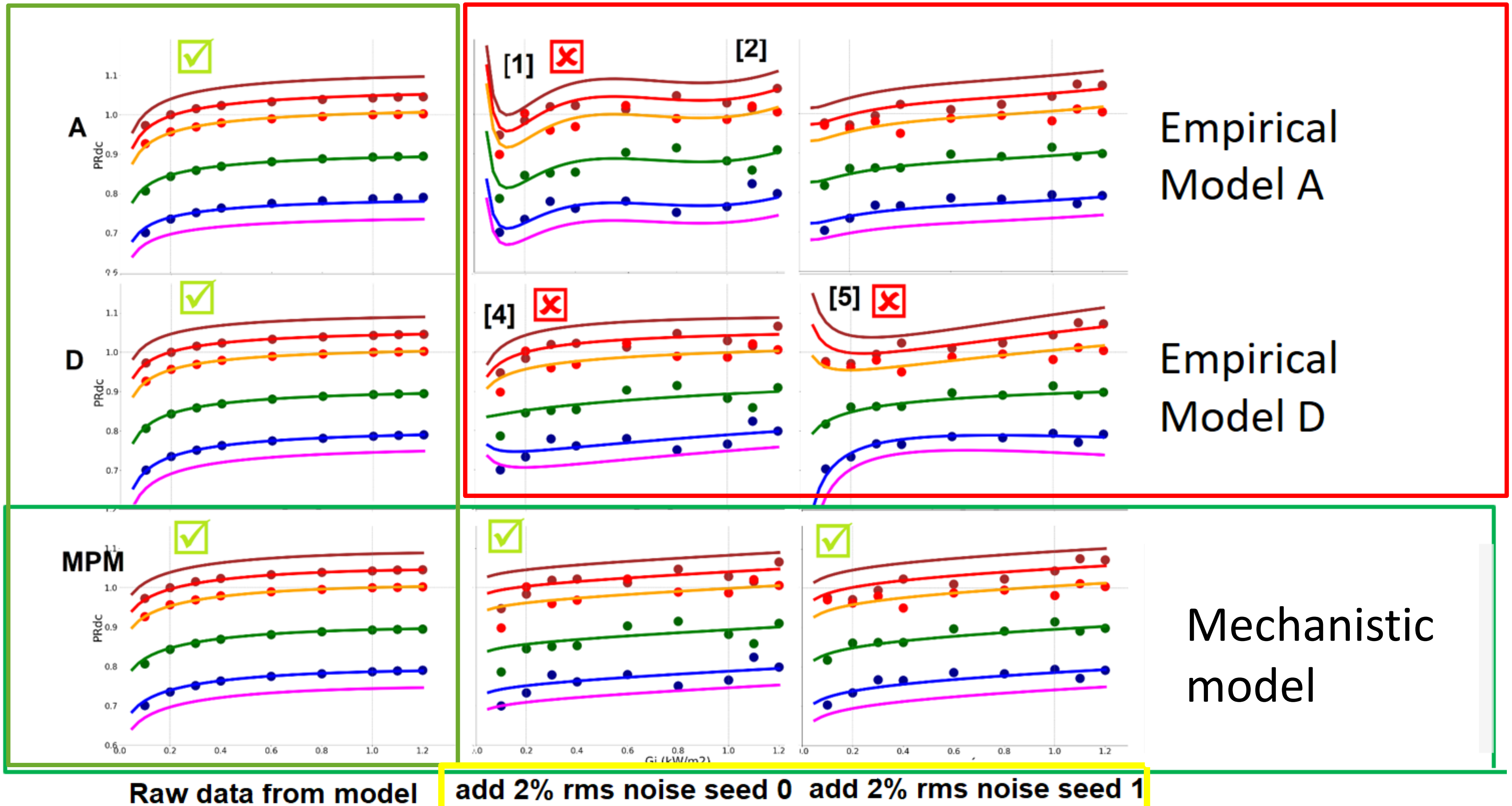
$P_{MAX.ACTUAL}$ — Temperature — Voc — R_{SERIES} — NOCT — «R_{SHUNT}»

MPM model has only "Meaningful, Orthogonal, Robust, Normalised" coefficients

Comparing Empirical and Mechanistic models (61853-1 matrix)

(PR_{DC} ⇧ vs. Irradiance ⇨ and T_{MODULE} coloured lines)

Compare fits to raw model data vs. 2% rms added noise to mimic measured data



Comparing Empirical and Mechanistic models (61853-1 matrix)

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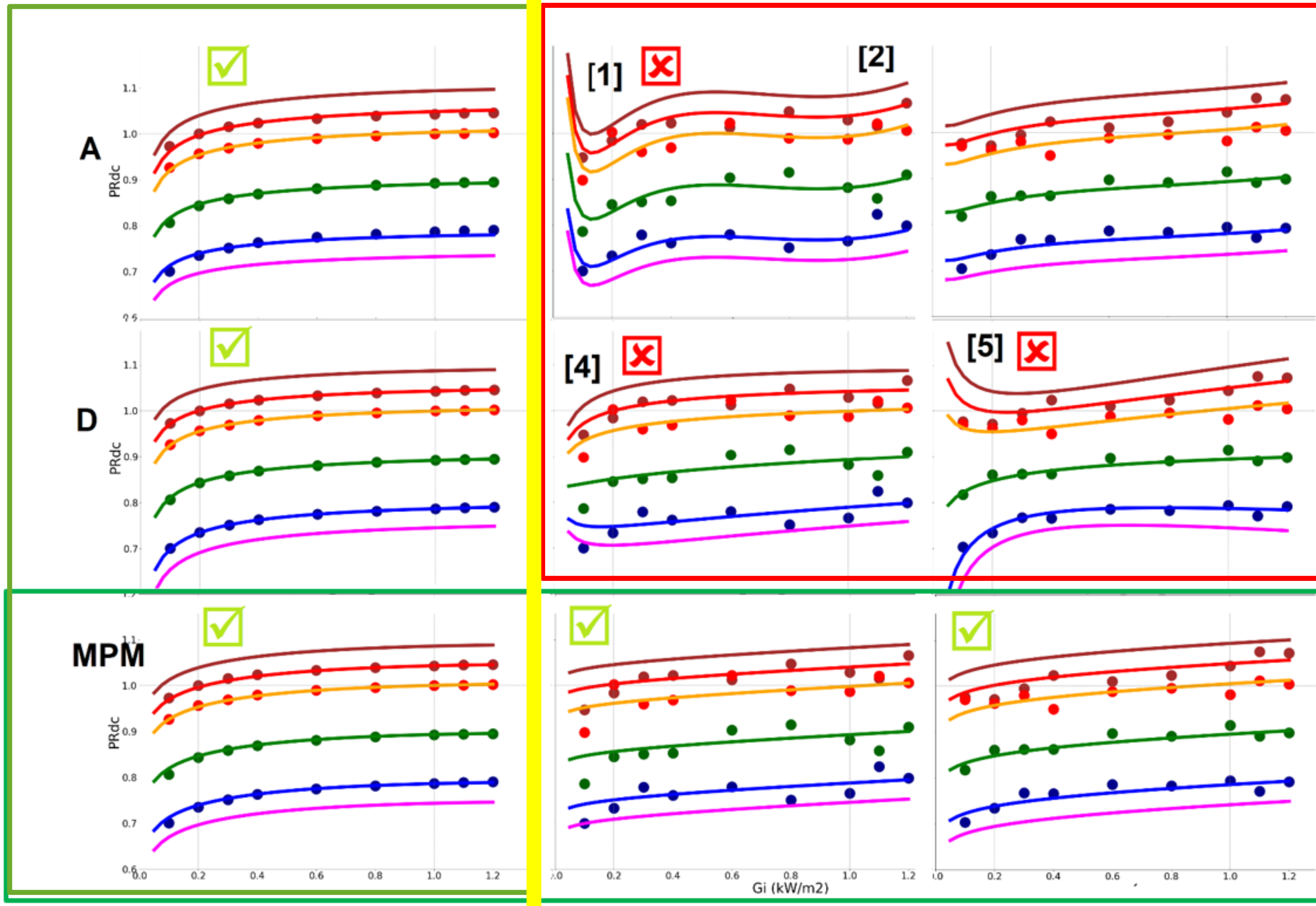
All fit "Perfect" data

Empirical Models don't fit "imperfect or noisy data" well



← [1] [2] Poor extrapolation and interpolation

← [4] [5] Variable temperature coefficient vs. irradiance

← ☑Mechanistic model always fits well, even to noisy data

Raw data from model | add 2% rms noise seed 0 | add 2% rms noise seed 1

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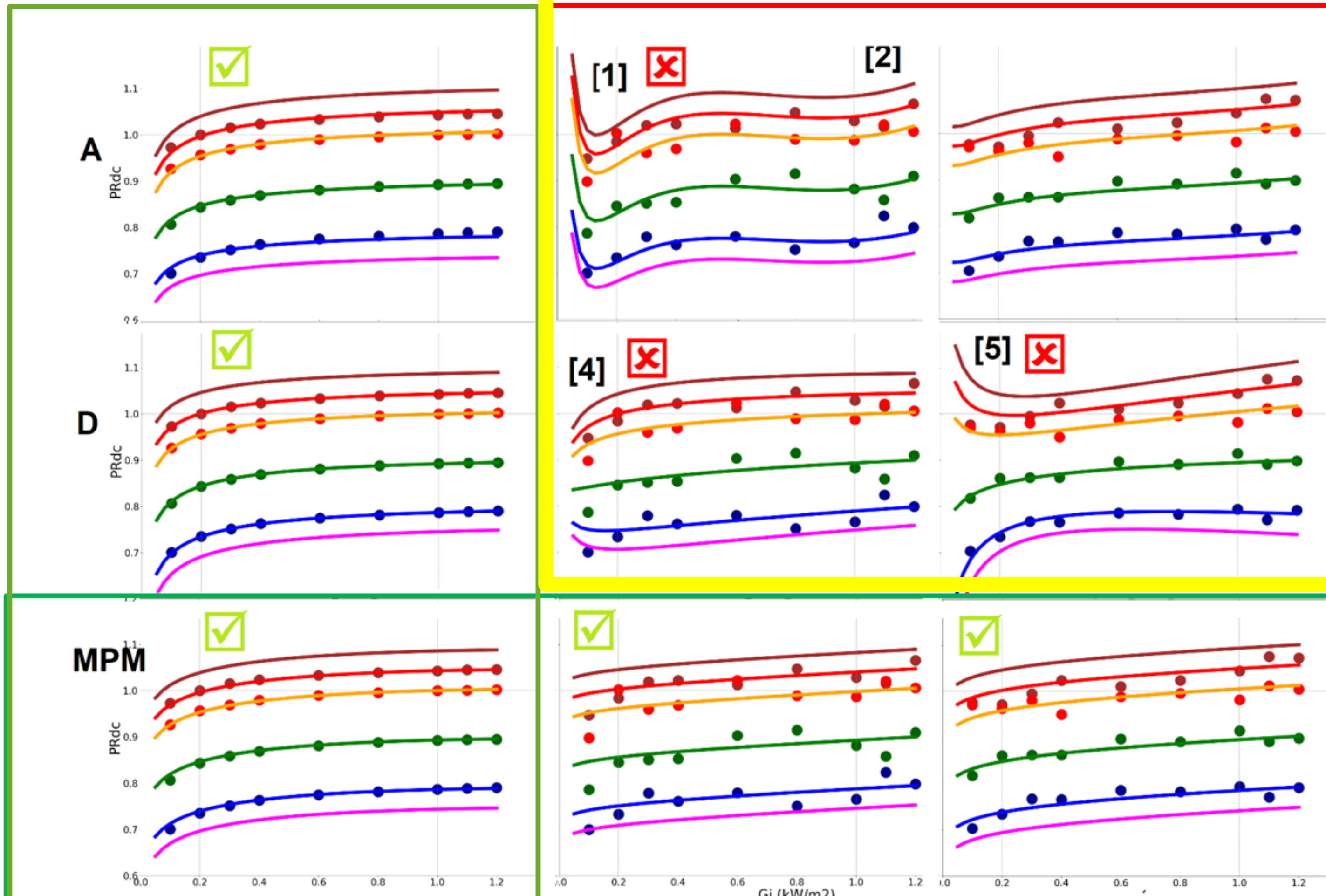

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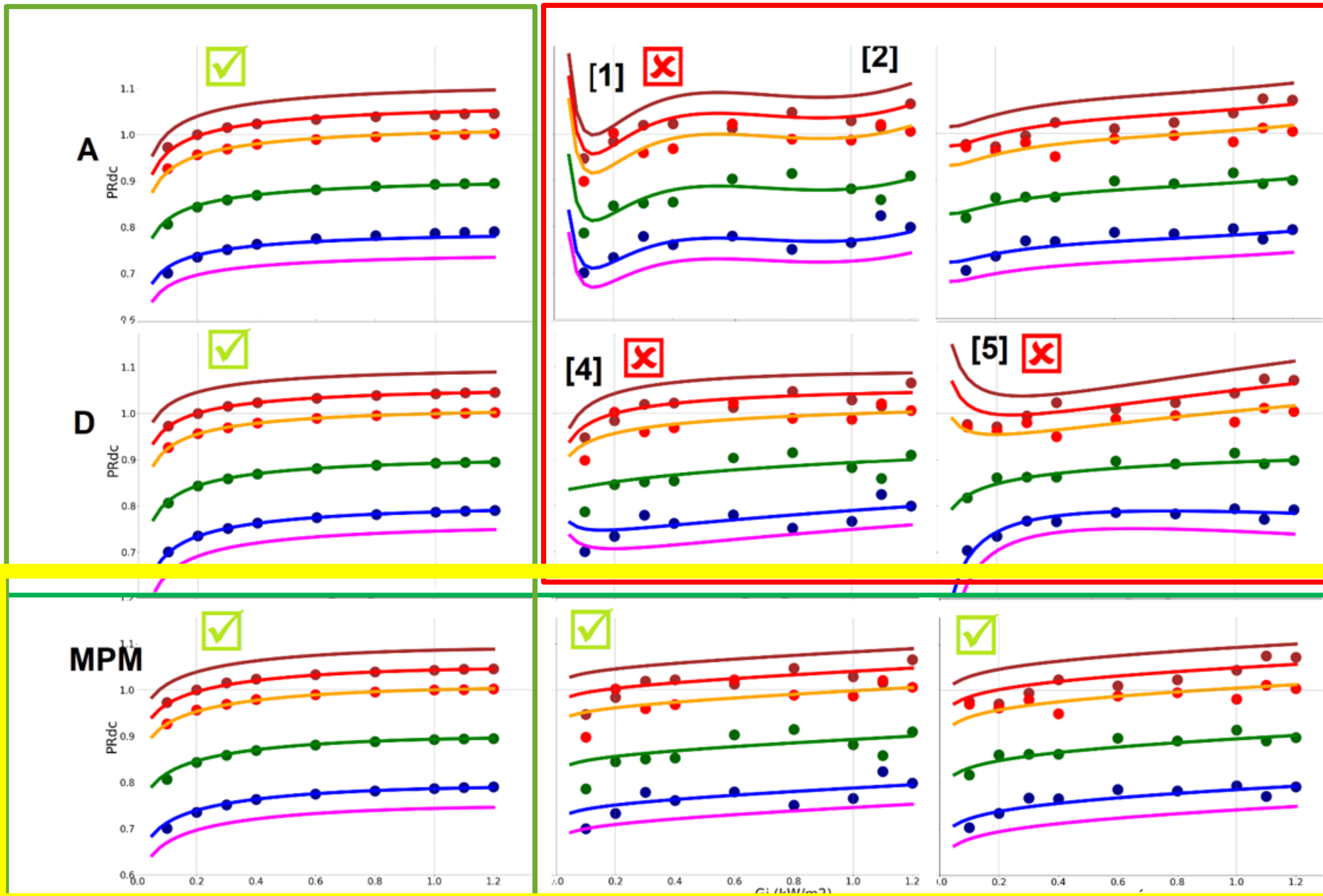

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Comparing model coefficients vs. technology cSi aSi CdTe

[SUPSI data]

Technology	ID	C_1	C_2	C_3	C_4	C_5	rms
c-Si	60) S	-42.3	53.9	-10.7	-32.9	-8.0	0.22%
c-Si	62) S	127.2	159.8	-31.7	-97.8	-23.9	0.22%
c-Si	64) S	-71.5	90.5	-18.0	-55.3	-13.5	0.09%
c-Si	66) S	-93.4	117.6	-23.4	-72.0	-17.6	1.84%
c-Si	67) S	100.2	123.8	24.6	75.6	18.4	0.24%
c-Si	68) S	-69.5	87.9	-17.5	-53.8	-13.1	0.16%
c-Si	70) S	-37.3	131.4	-98.7	21.9	23.5	0.10%
c-Si	71) S	6.4	-6.8	1.4	4.1	0.9	0.07%
c-Si	72) S	60.7	132.5	76.7	10.1	-10.2	0.59%
c-Si	73) S	53.8	-68.9	16.3	38.4	8.7	0.09%
TF a-Si	65) S	0.2	1.1	-0.3	-0.5	-0.1	0.94%
TF a-Si	74) S	90.8	121.1	31.9	62.8	13.2	0.32%
TF CdTe	63) S	-0.6	2.2	-0.6	-1.2	-0.3	0.27%

Empirical model

No pattern to coefficients even though fits are reasonable and c-Si measurements were quite similar

Technology	ID	C_1	C_2	C_3	C_4	C_5	rms
c-Si	60) S	96.2%	-0.45%	8.3%	-2.1%	0.0%	0.07%
c-Si	62) S	109.6%	-0.42%	20.5%	-10.0%	0.0%	0.09%
c-Si	64) S	106.4%	-0.45%	8.5%	-6.4%	0.0%	0.09%
c-Si	66) S	107.7%	-0.48%	11.9%	-7.7%	0.0%	0.08%
c-Si	67) S	115.2%	-0.48%	18.2%	-15.4%	0.0%	0.11%
c-Si	68) S	107.6%	-0.47%	10.4%	-7.5%	0.0%	0.09%
c-Si	70) S	103.7%	-0.46%	3.9%	-4.3%	0.0%	0.08%
c-Si	71) S	113.7%	-0.46%	24.4%	-12.4%	0.0%	0.08%
c-Si	72) S	99.6%	-0.44%	0.7%	1.2%	0.0%	0.20%
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TF CdTe	63) S	121.3%	-0.23%	19.6%	-20.2%	0.0%	0.16%

MPM Mechanistic model

Sensible values of all coefficients = more robust

P_{MAX} tolerance ↗ ↖ Realistic P_{MAX} Temperature coefficient etc.

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Sensible values of all coefficients = more robus

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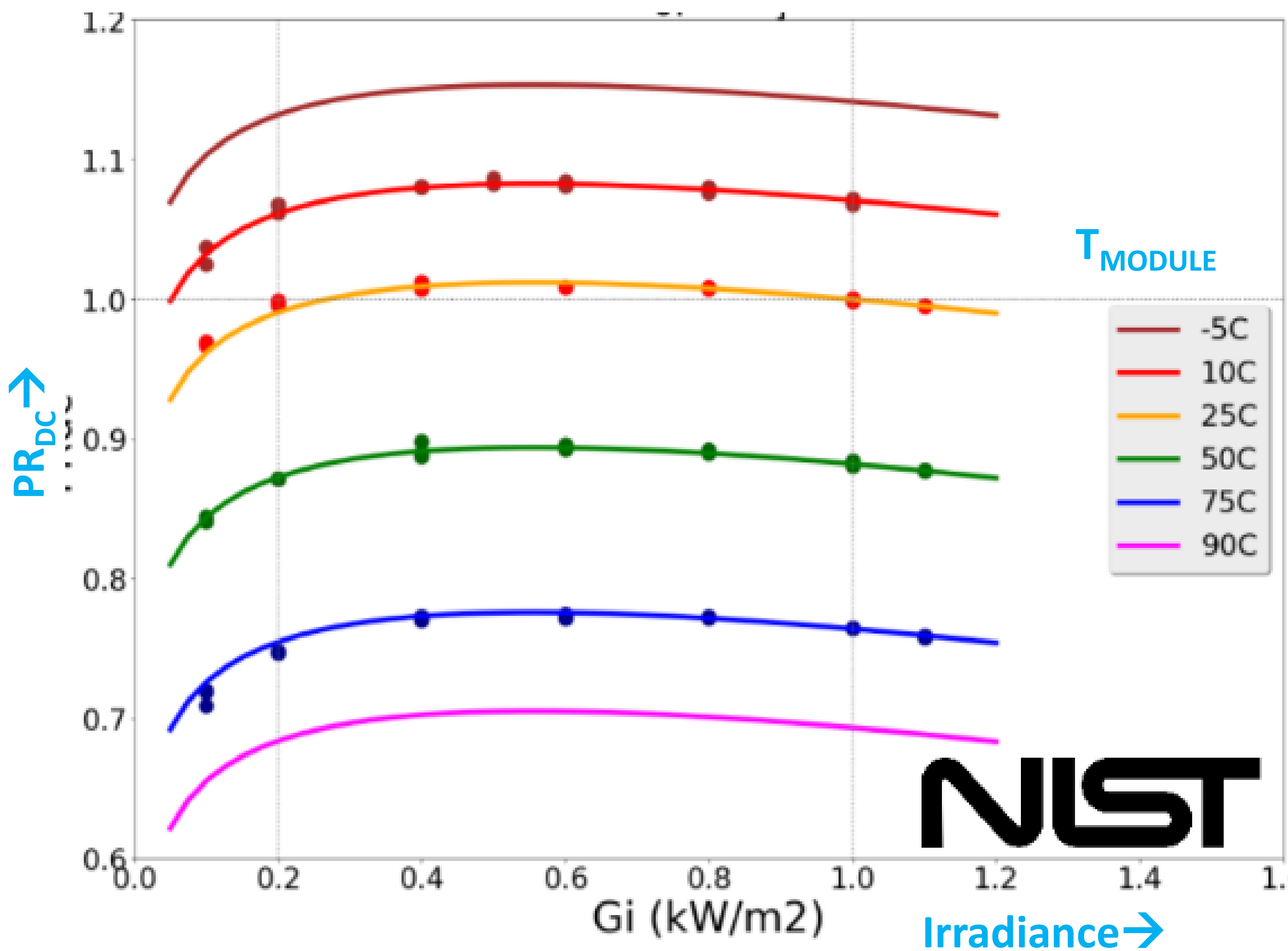
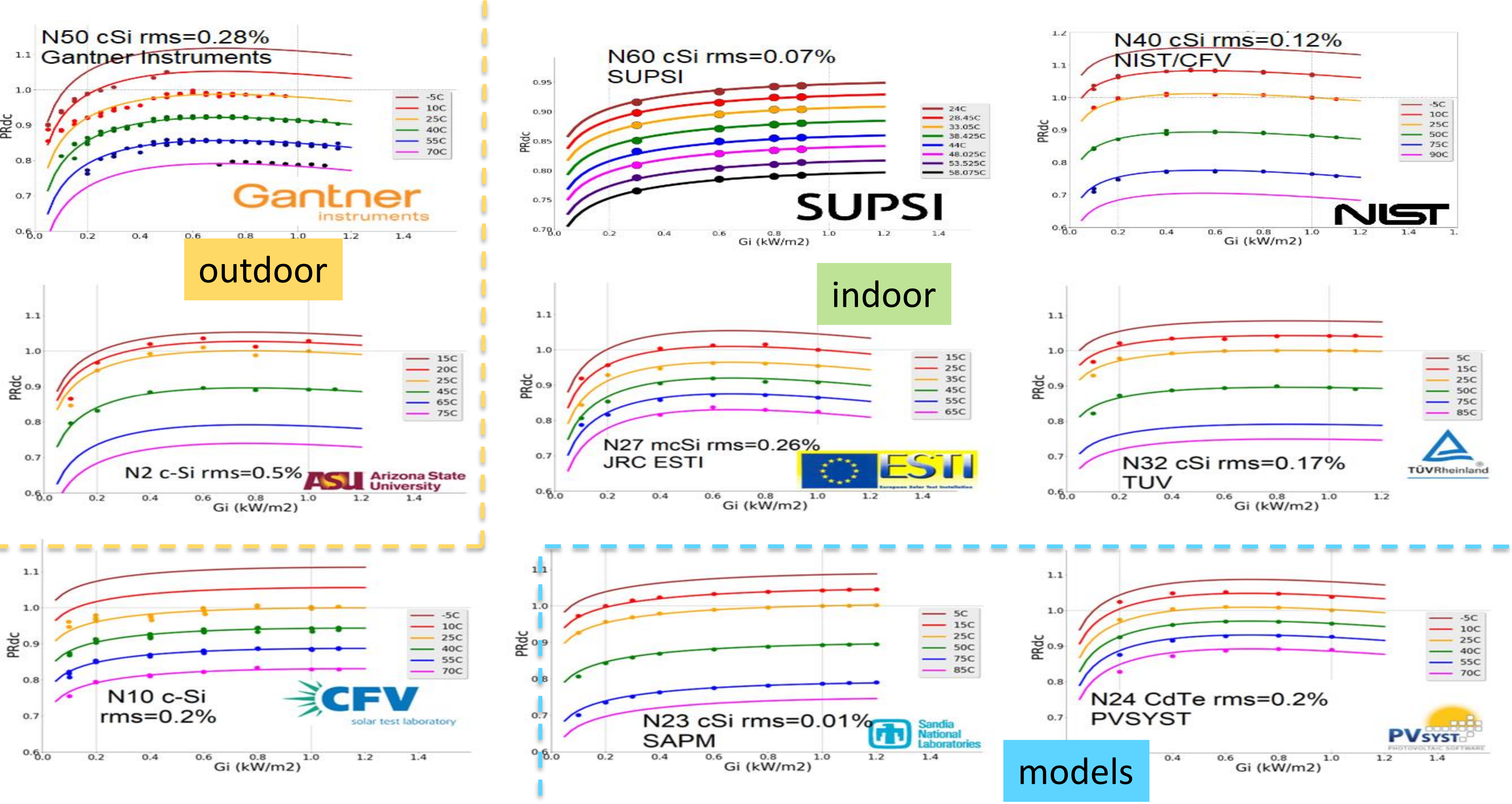
How well can MPM fit IEC 61853-1 data?

Typical c-Si data from NIST/CFV has an rms error of 0.12%



MPM can easily fit 3rd party indoor, outdoor and models

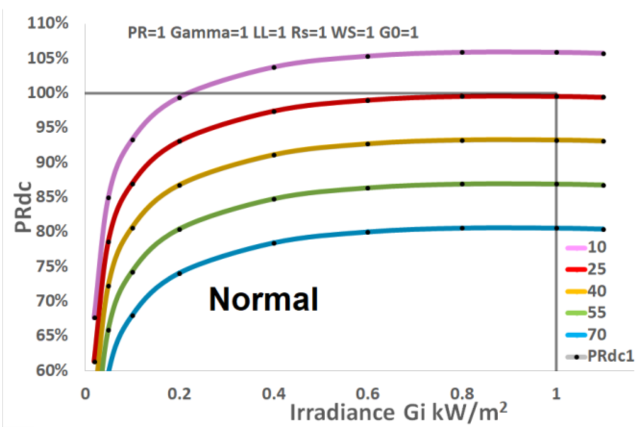
Data From Gantner, SUPSI, NIST, ASU, ESTI, TUV Rheinland, CFV, SAPM and PVSYST

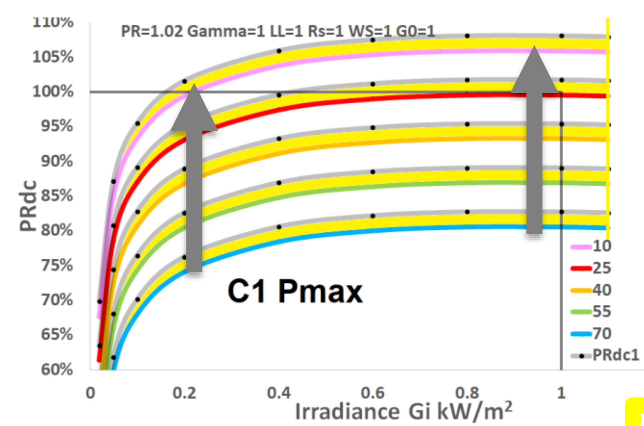


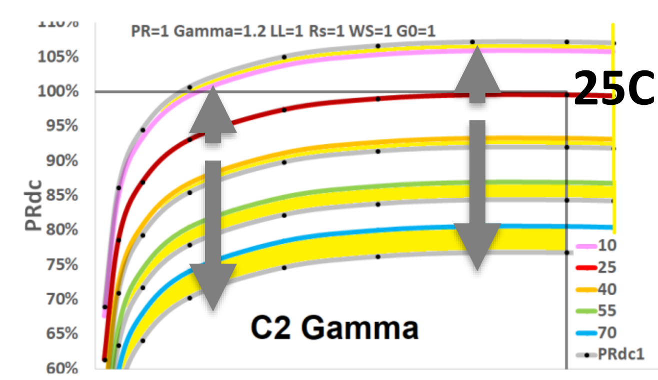
Are all the model coefficients independent?

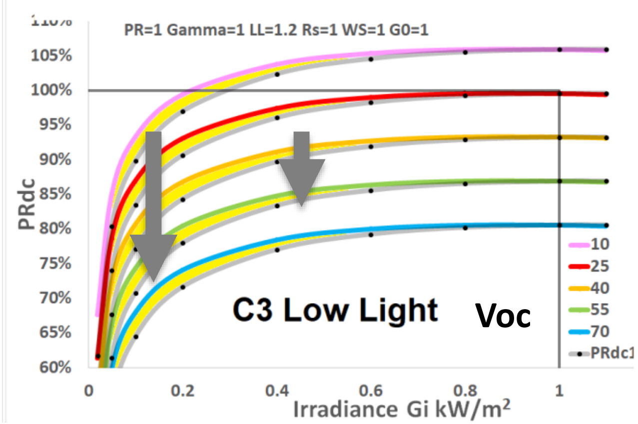
$C_1 + C_2*dT_{MOD} + C_3*\log(G_I) + C_4*G_I + (C_5*WS + \cancel{(C_6/G_I)})$

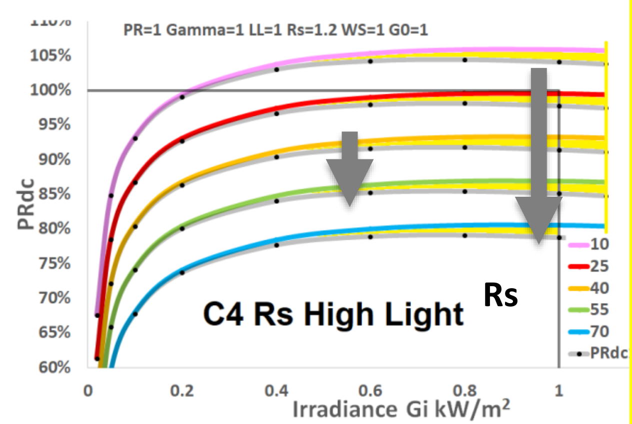
$P_{MAX.ACTUAL}$ Gamma Voc R_{SERIES} NOCT «R_{SHUNT}»











If we alter each coefficient individually - all traces should change differently

These graphs do that so the MPM has unique fits and is robust

Irradiance Gi kW/m²

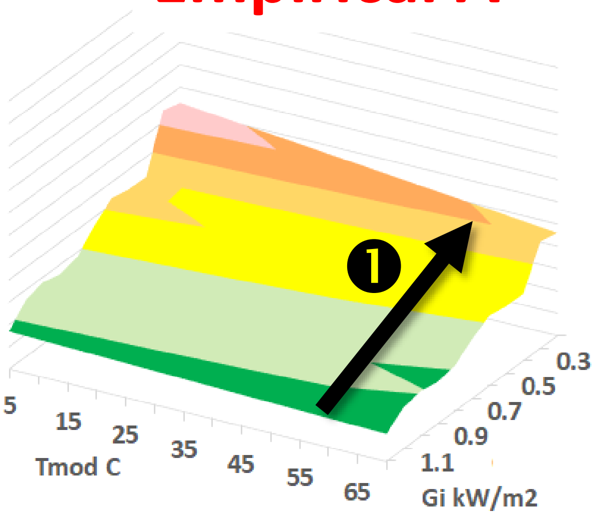
Investigating energy yield

- **How does the robustness and variability of a model fit affect its energy yield predictions?**

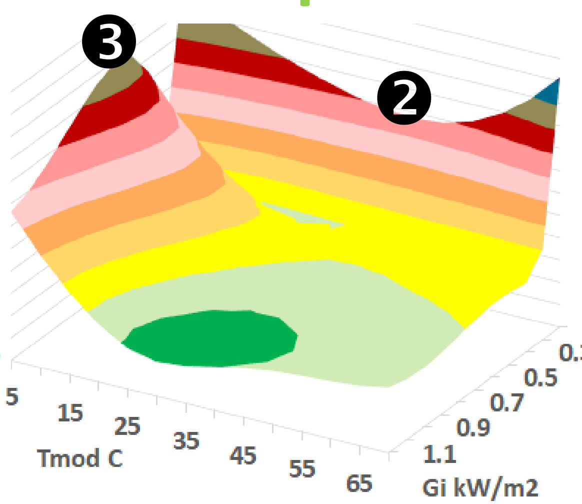
- **Consider fit variability at low and high light levels and temperatures with sites that are dull, bright, cold or hot.**

How do the model fits vary vs. T_{MOD} ↘ and irradiance ↙ bins?

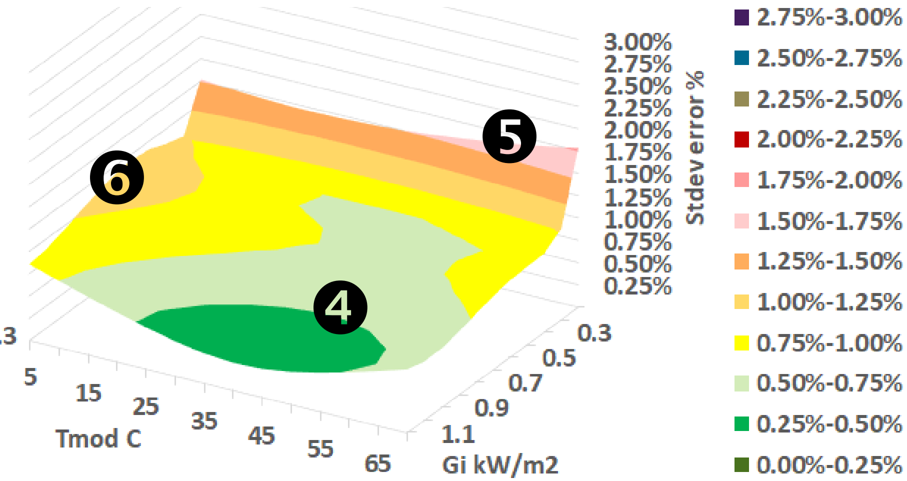
Empirical A



Empirical D



MPM



➊ Decline in accuracy as irradiance falls

➋ Variable at low light

➌ Poor at Cold+Mid light levels

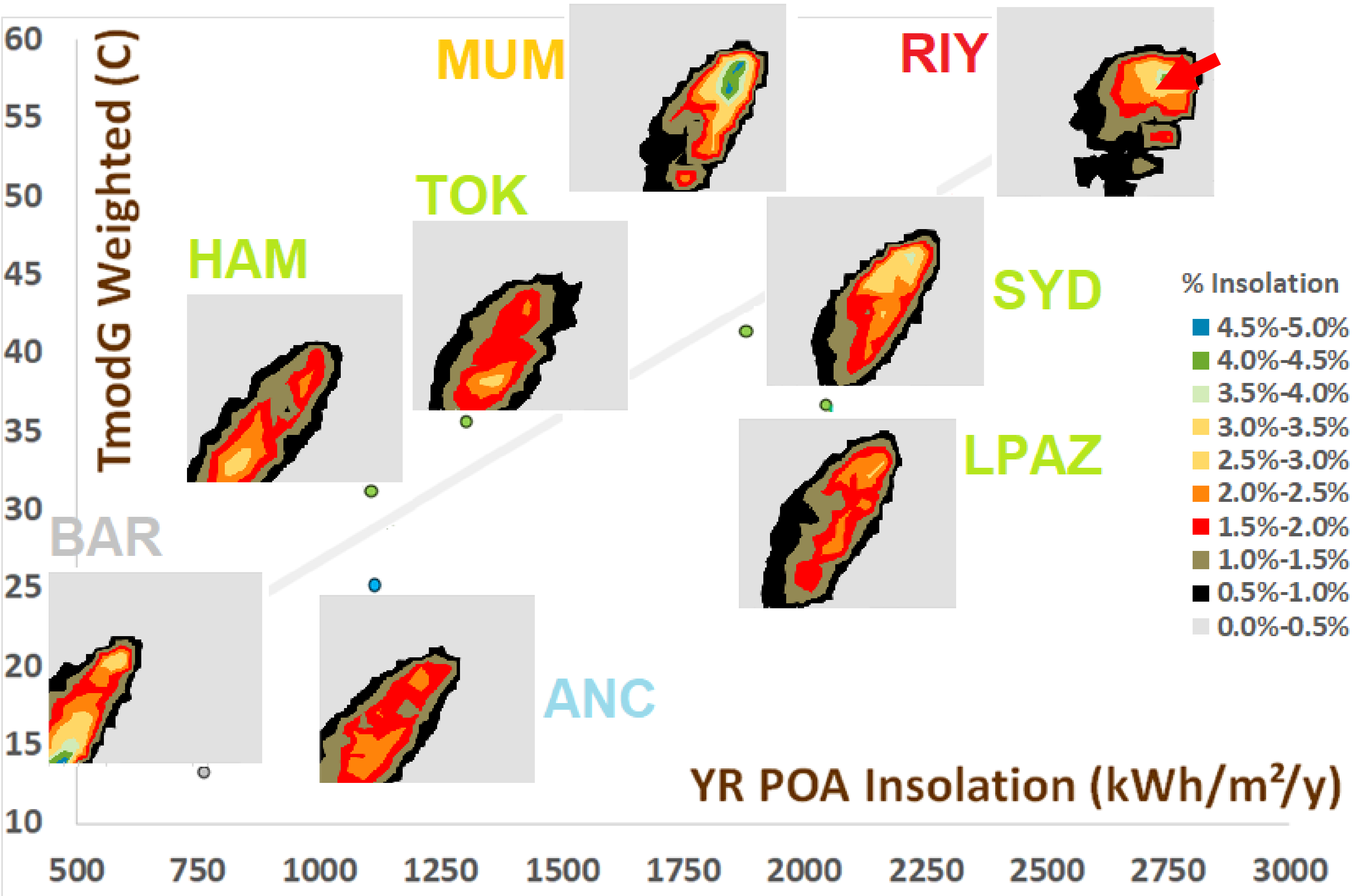
➍ Good almost everywhere

Only slightly worse at

➎ lowest light or

➏ cold+mid light levels

Insolation fraction vs.Irradiance ➔ and Module Temperature ⬆ varies for sites worldwide – Koeppen colours



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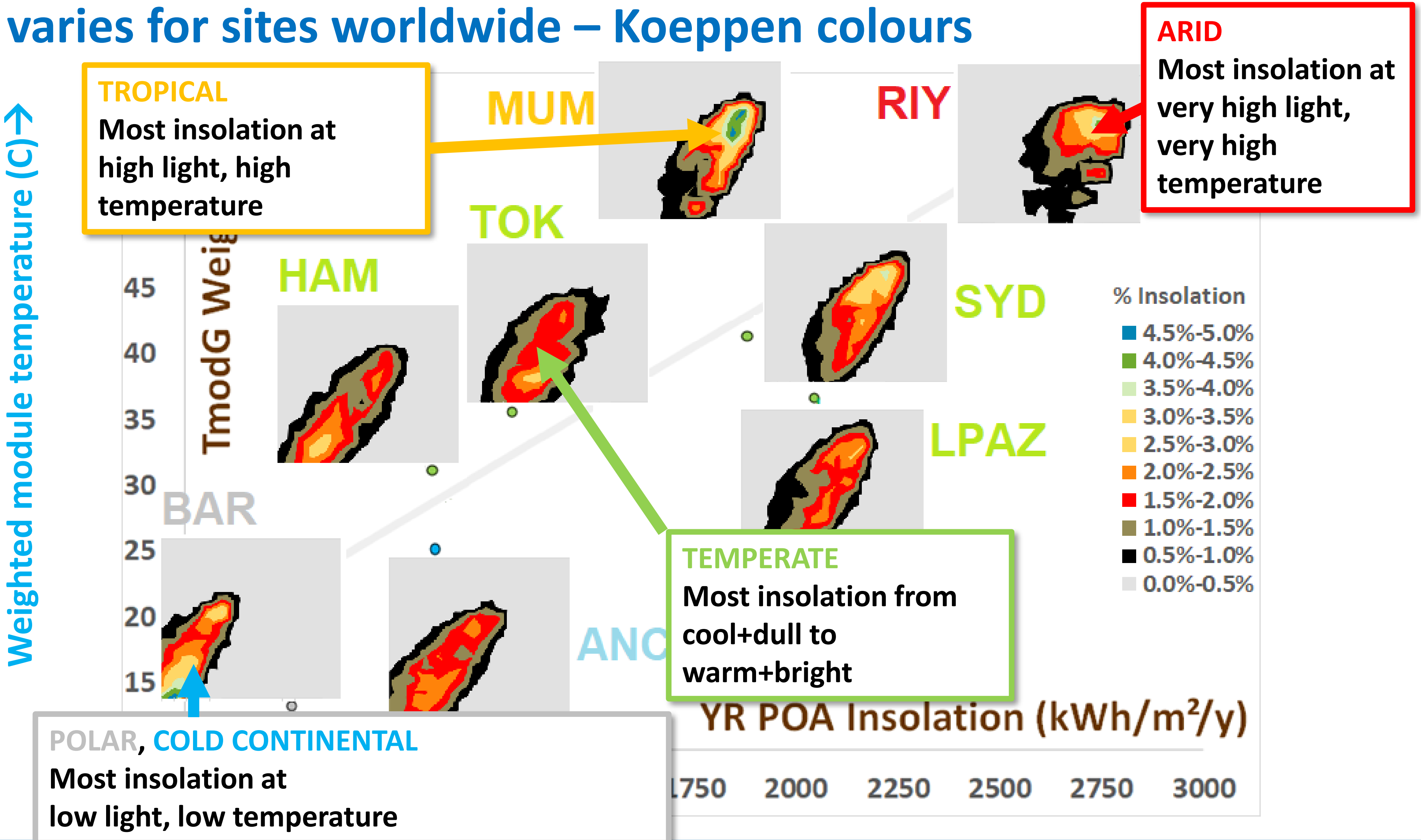

Energy Yield predicted variability by site

- Polar to Arid

- Each site has rms error for
  1) Summer month (Jul or Jan)
  2) Winter month (Jan or Jul)
  3) Yearly Average (All 12 months)
- The most robust model should have lowest rms error everywhere

Site name, Koeppen climate designation		A	D	MPM
BARENTSBERG	Summer	1.09%	0.77%	0.40%
Polar Tundra Eternal winter (ice cap)	Winter			
Etf	Year	1.21%	0.72%	0.36%
ANCHORAGE	Summer	0.50%	0.30%	0.25%
Cold (continental) Without dry season Cold summer	Winter	1.14%	0.96%	0.44%
Dfc	Year	0.54%	0.29%	0.27%
HAMBURG	Summer	0.40%	0.33%	0.23%
Temperate Without dry season Warm summer	Winter	1.89%	0.82%	0.41%
Cfb	Year	0.55%	0.32%	0.25%
TOKYO	Summer	0.43%	0.37%	0.28%
Temperate Without dry season Hot summer	Winter	0.31%	0.28%	0.30%
Cfa	Year	0.36%	0.28%	0.25%
SYDNEY	Summer	0.23%	0.33%	0.23%
Temperate Without dry season Hot summer	Winter	0.34%	0.28%	0.27%
Cfa	Year	0.25%	0.31%	0.23%
LA PAZ	Summer	0.30%	0.26%	0.22%
Temperate Dry winter Warm summer	Winter	0.18%	0.23%	0.17%
Cwb	Year	0.22%	0.24%	0.19%
MUMBAI	Summer	0.44%	0.39%	0.29%
Tropical Savanna, Wet	Winter	0.21%	0.35%	0.28%
Aw	Year	0.23%	0.35%	0.28%
RIYADH	Summer	0.24%	0.36%	0.36%
Arid Desert Hot	Winter	0.21%	0.29%	0.21%
Bwh	Year	0.21%	0.32%	0.27%
AVERAGE 22 SITES	Summer	**0.33%**	**0.36%**	**0.27%**
	Winter	**0.56%**	**0.42%**	**0.29%**
	Year	**0.35%**	**0.33%**	**0.25%**

Conclusions

Existing empirical models

☒ Can't repeatably fit imperfect data. They have unphysical coefficients.

Mechanistic Performance Model (MPM)

☑ Much more robust and useful than empirical fit models

☑ Added to Gantner Instruments' www.gantner-webportal.com SaaS platform

Energy yield predictions

☑ Much less variability in EY from fitting errors for MPM
MPM 0.25-0.29% vs. Empirical 0.33-0.56%

$$PR_{DC} = \underbrace{C_1}_{P_{MAX.ACTUAL}} + \underbrace{C_2 * (T_{MOD} - 25)}_{Temperature} + \underbrace{C_3 * Log_{10}(G_I)}_{Voc} + \underbrace{C_4 * G_I}_{R_{SERIES}} + \underbrace{C_5 * WS}_{NOCT} + \underbrace{\cancel{(C_6 / G_I)}}_{«R_{SHUNT}»}$$

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See Poster 7TuPo.225

Quantifying and analysing the variability of PV module resistances R_{SC} and R_{OC} to understand and optimise kWh/kWp modelling

Thank you for your attention!

- Please contact me to share your data steve@steveransome.com