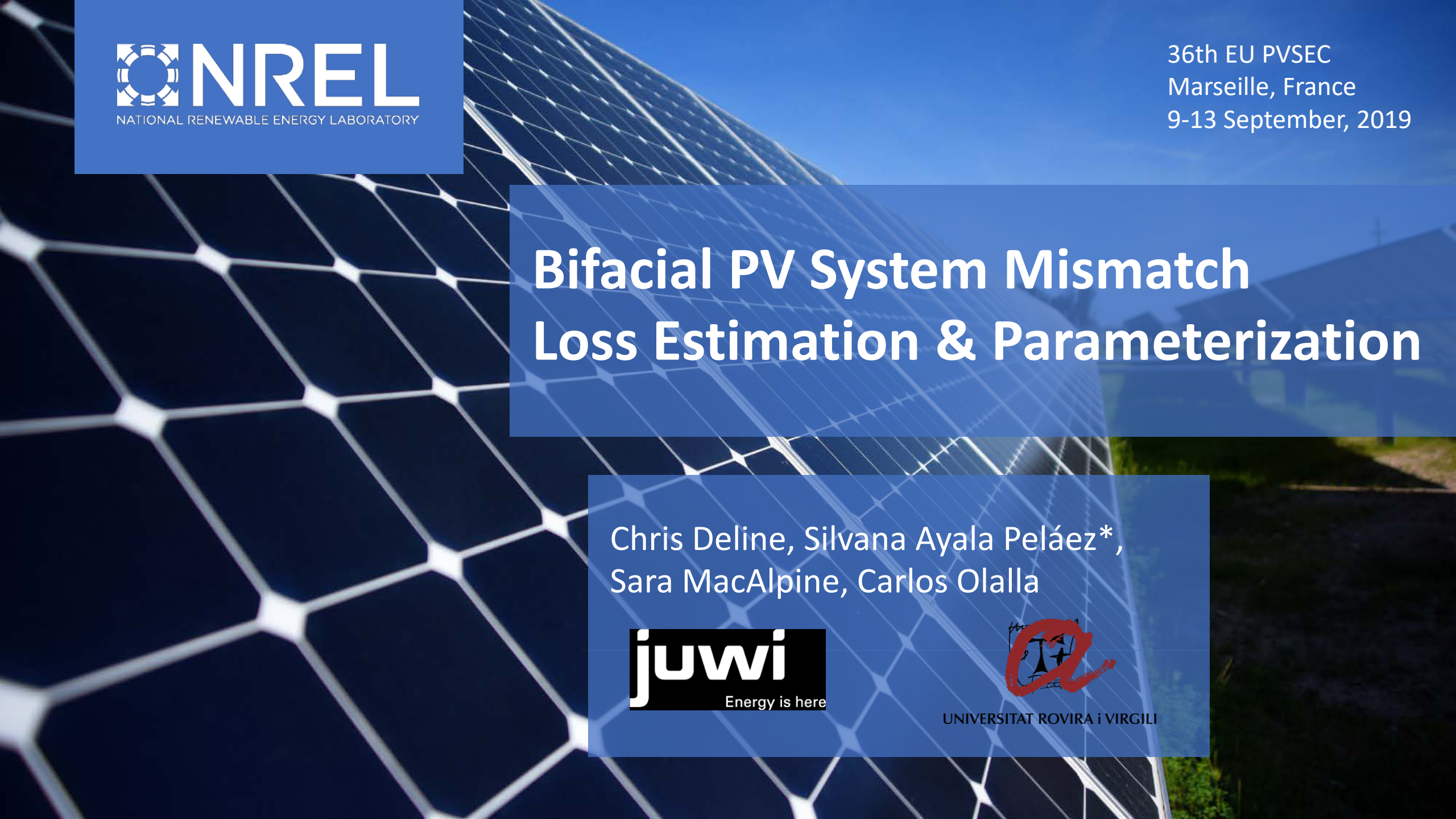


NREL
NATIONAL RENEWABLE ENERGY LABORATORY

36th EU PVSEC
Marseille, France
9-13 September, 2019

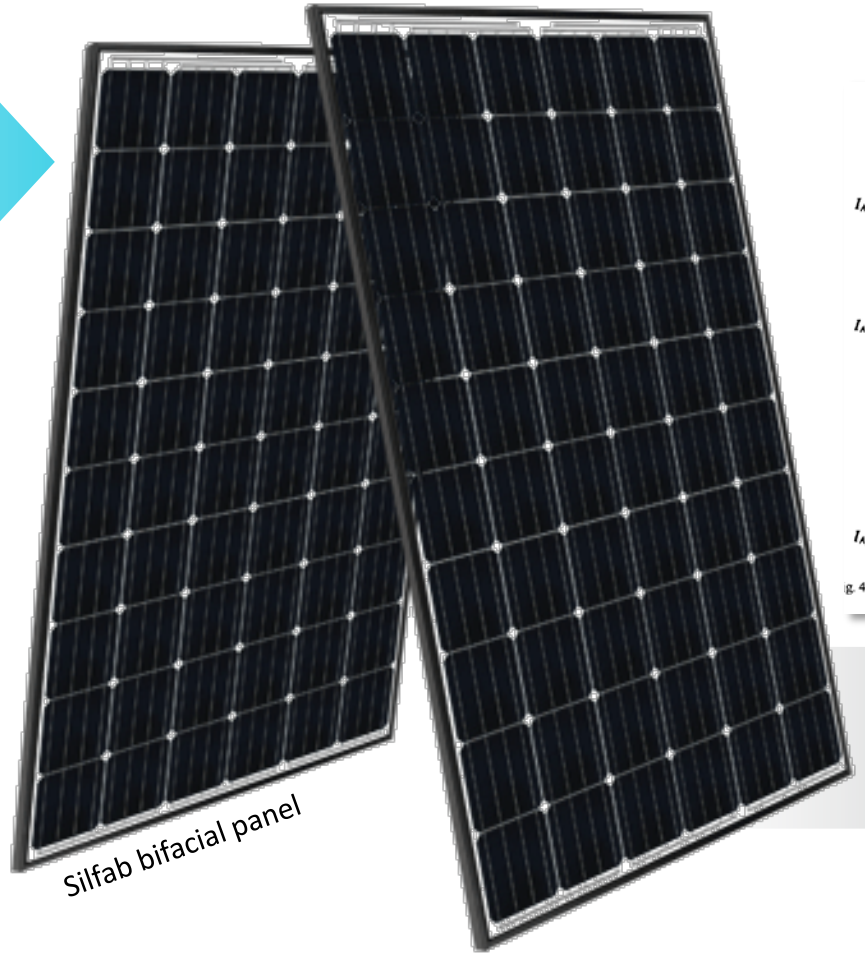
Bifacial PV System Mismatch Loss Estimation & Parameterization

Chris Deline, Silvana Ayala Peláez*,
Sara MacAlpine, Carlos Olalla

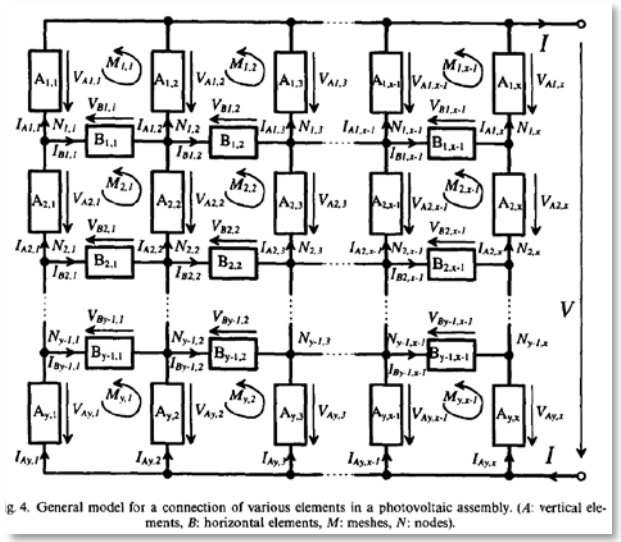
juwi
Energy is here

UNIVERSITAT ROVIRA i VIRGILI

Irradiance Distribution



Silfab bifacial panel



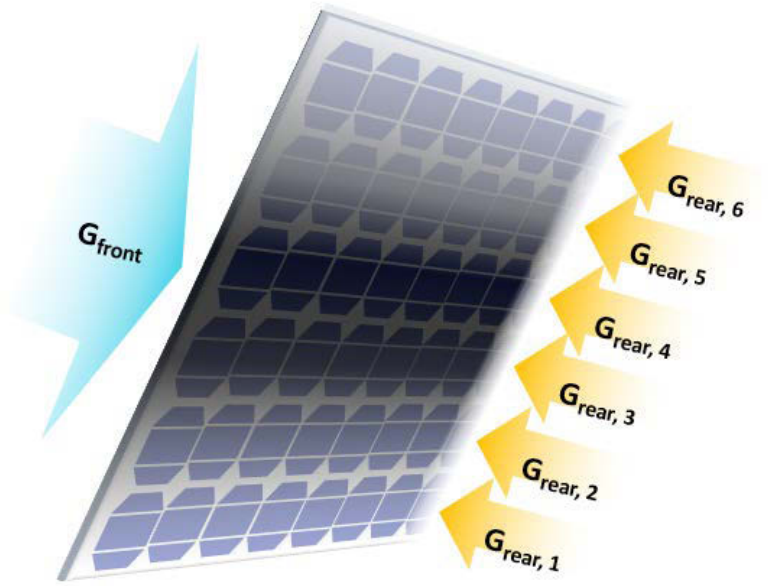
g. 4. General model for a connection of various elements in a photovoltaic assembly. (*A*: vertical elements, *B*: horizontal elements, *M*: meshes, *N*: nodes).

Power output
*Mismatch loss

Reduced Order Model

*V. Quaschning, R. Hanitsch 1996

Electrical Mismatch



G_{total} W/m²

1059

976

967

986

1034

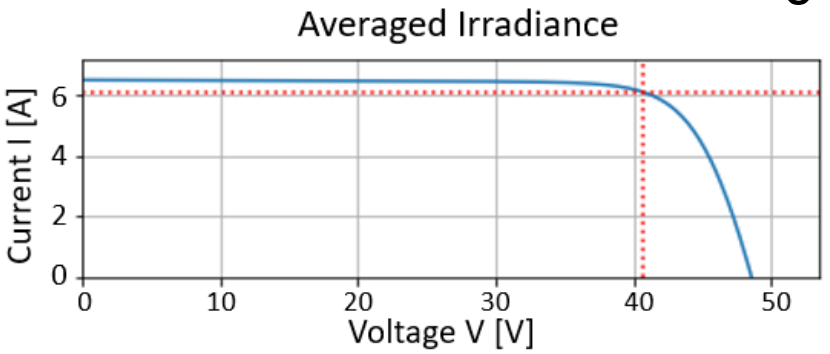
1128

Cairo, June 21st at 2 PM

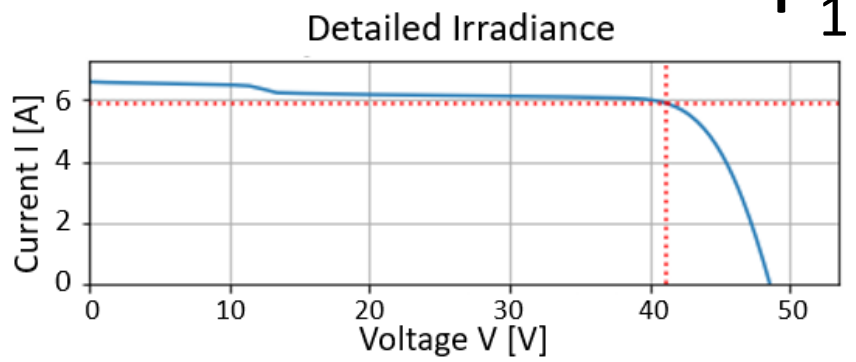
Averaging Irradiance for the module ~1031 W/m²

Detailed Irradiance value

P_0

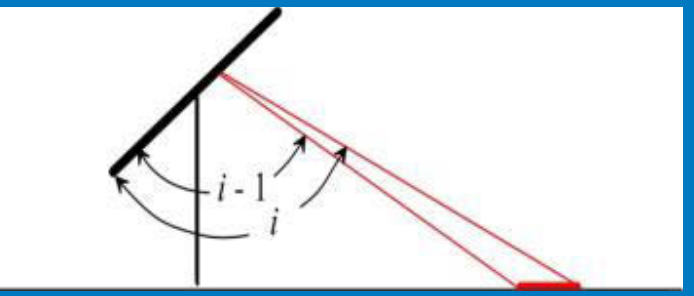


P_1



$$L_{DC} = M = 1 - \frac{P_1}{P_0}$$

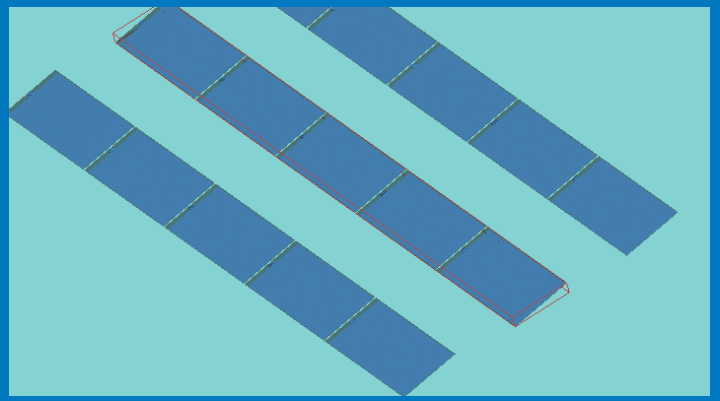
Irradiance Model

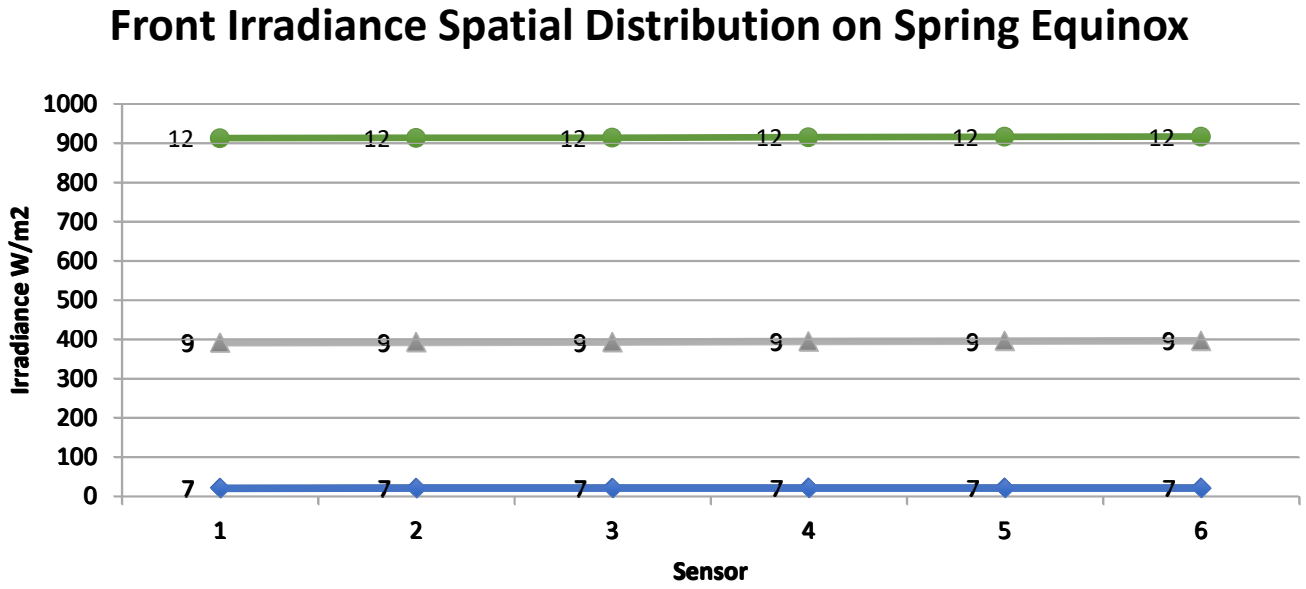


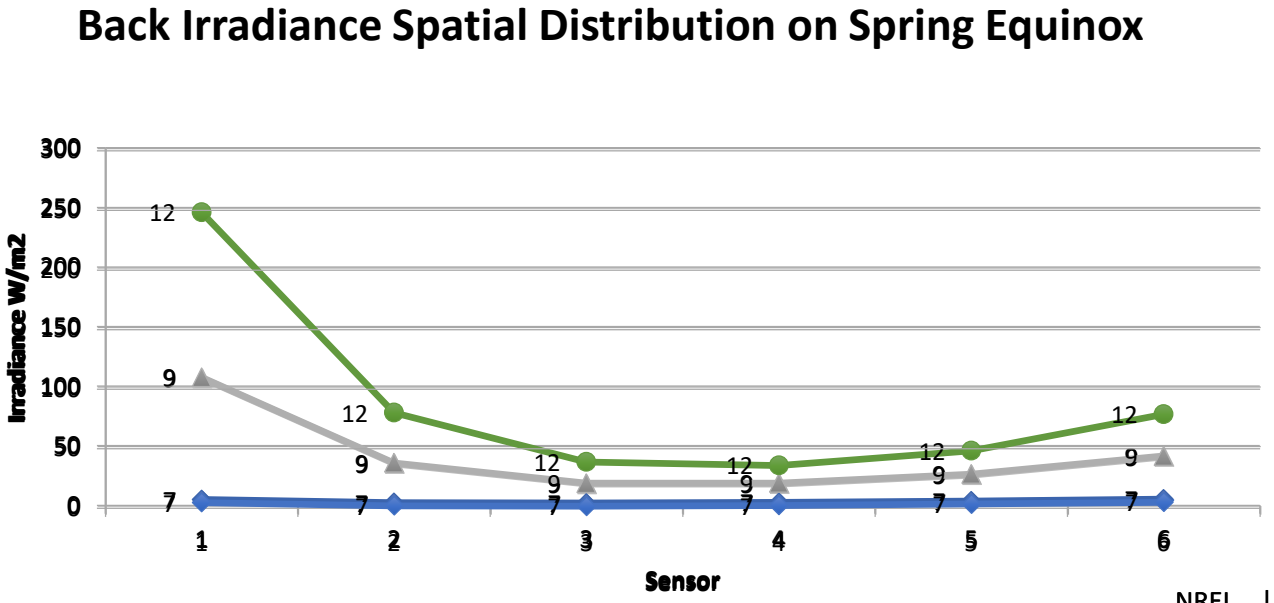
bifacialVF

or

bifacial_radiance



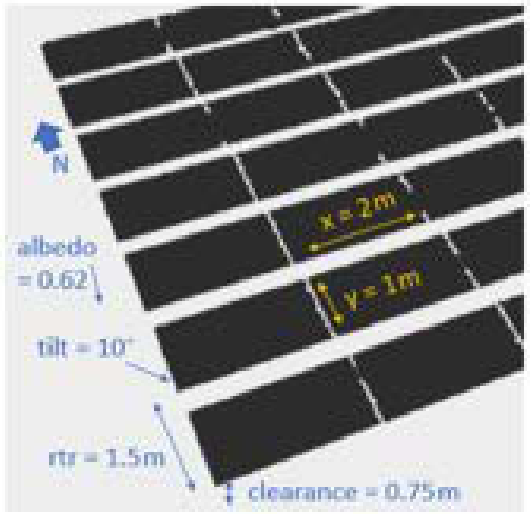




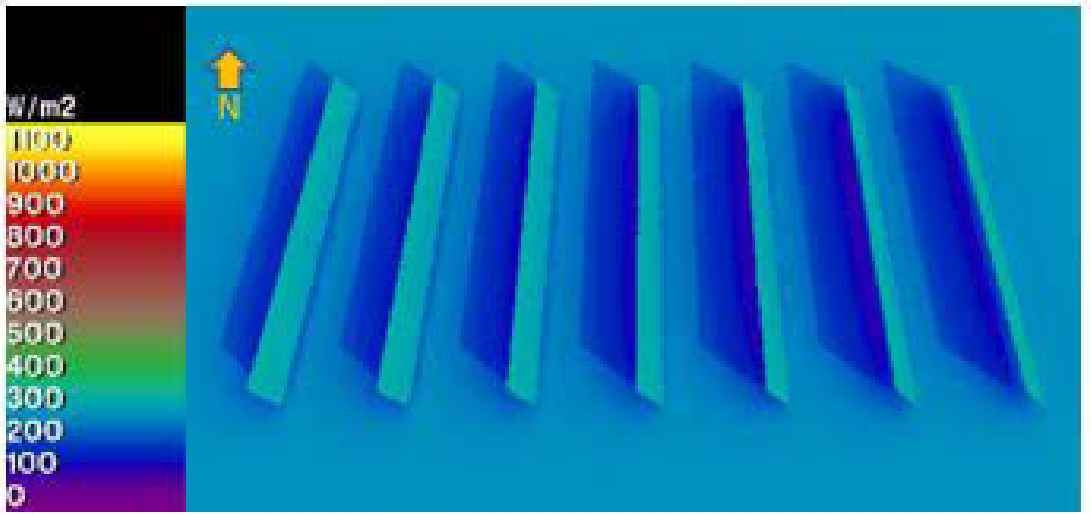
Scenarios

System	Height	Albedo	GCR	Tilt	# modules
a) Rooftop	0.15 – 1 m	0.62	0.67	10°	1-landscape
b) Tracking c) Tracking w TT	1.0 – 2.4 m	0.2	0.33	--	1-portrait

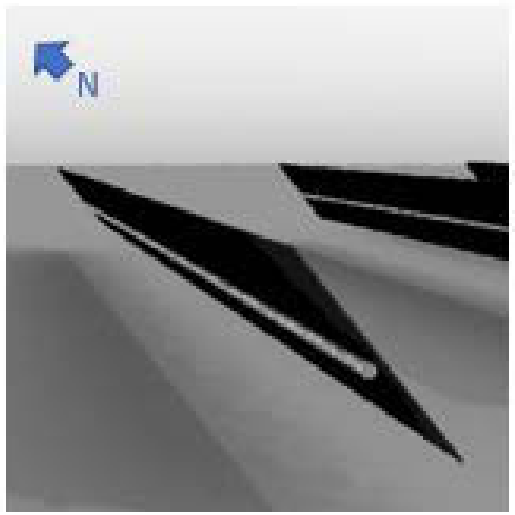
a)



b)



c)



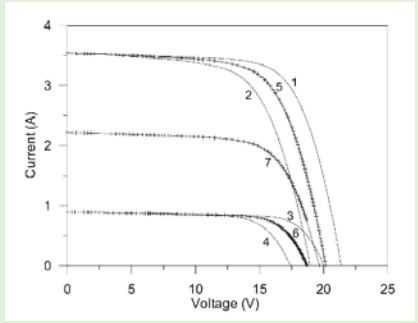
Electrical Model

PV Mismatch

SUNPOWER®

Cell > Module > String > System
2-diode system; Irrad. and Temperature inputs

Bilinear Interpolation

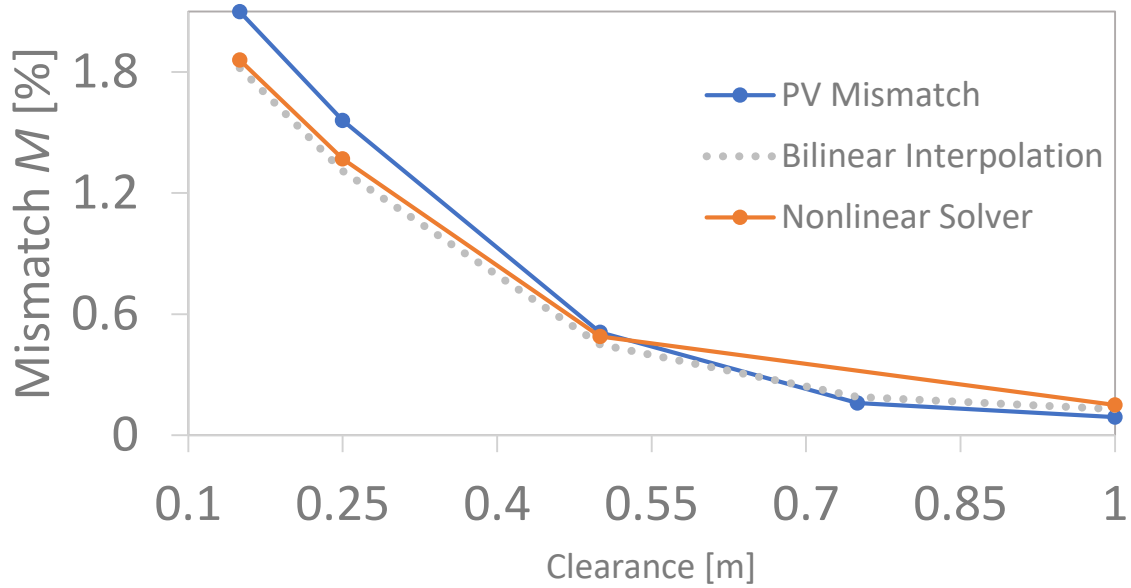


Nonlinear Solver

$$\begin{bmatrix} f_1 \\ \vdots \\ f_{n_s} \\ f_{n_s+1} \end{bmatrix} = \begin{bmatrix} I_{\mathrm{str}} - I_{\mathrm{cell}_1} - I_{\mathrm{by}_1} = 0 \\ \vdots \\ I_{\mathrm{str}} - I_{\mathrm{cell}_{n_s}} - I_{\mathrm{by}_{n_s}} = 0 \\ \sum_{j=1}^{n_s} V_{\mathrm{sub}_j} - V_{\mathrm{str}} = 0. \end{bmatrix}$$

System of n_s+1 equations and n_s+1 unknowns.
Use Nonlinear Newton-Raphson solver

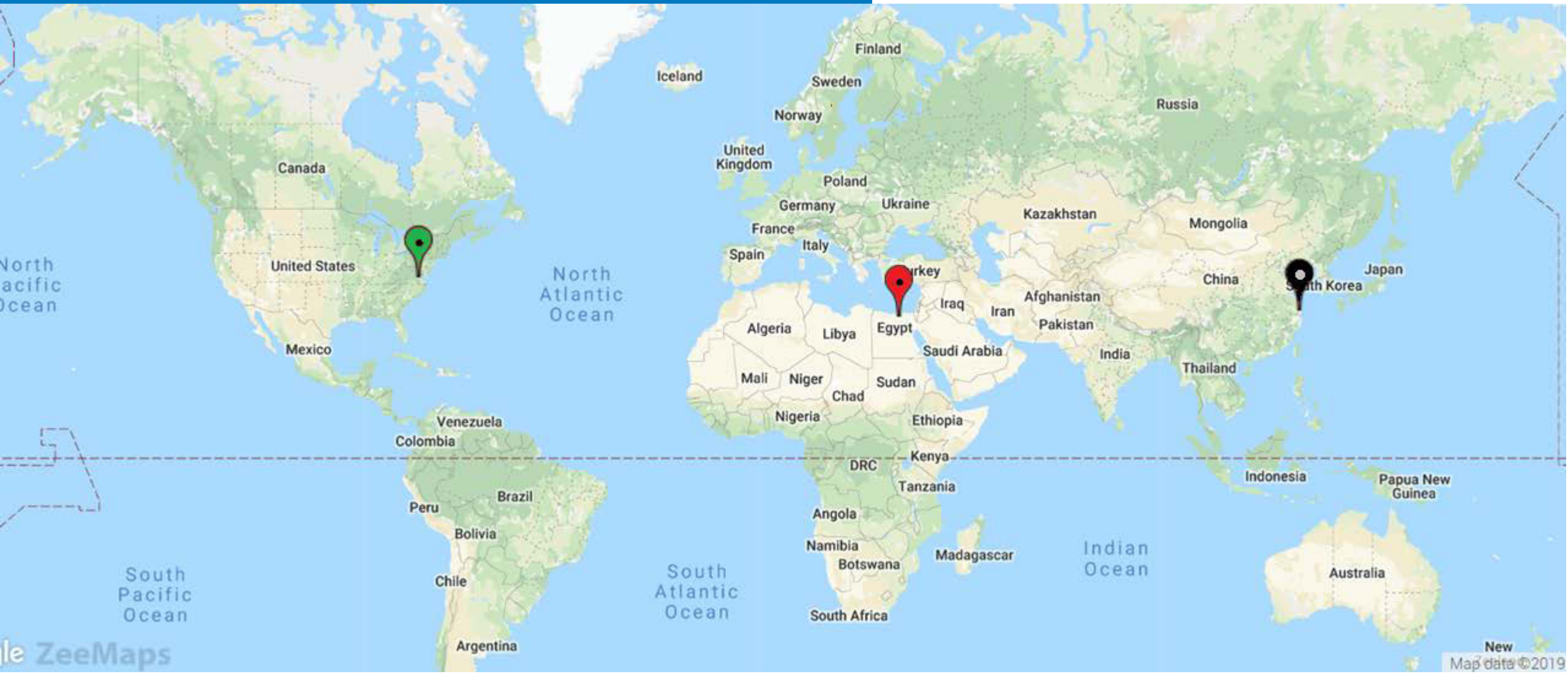
Outcome of calculated mismatch loss % was found to be similar.



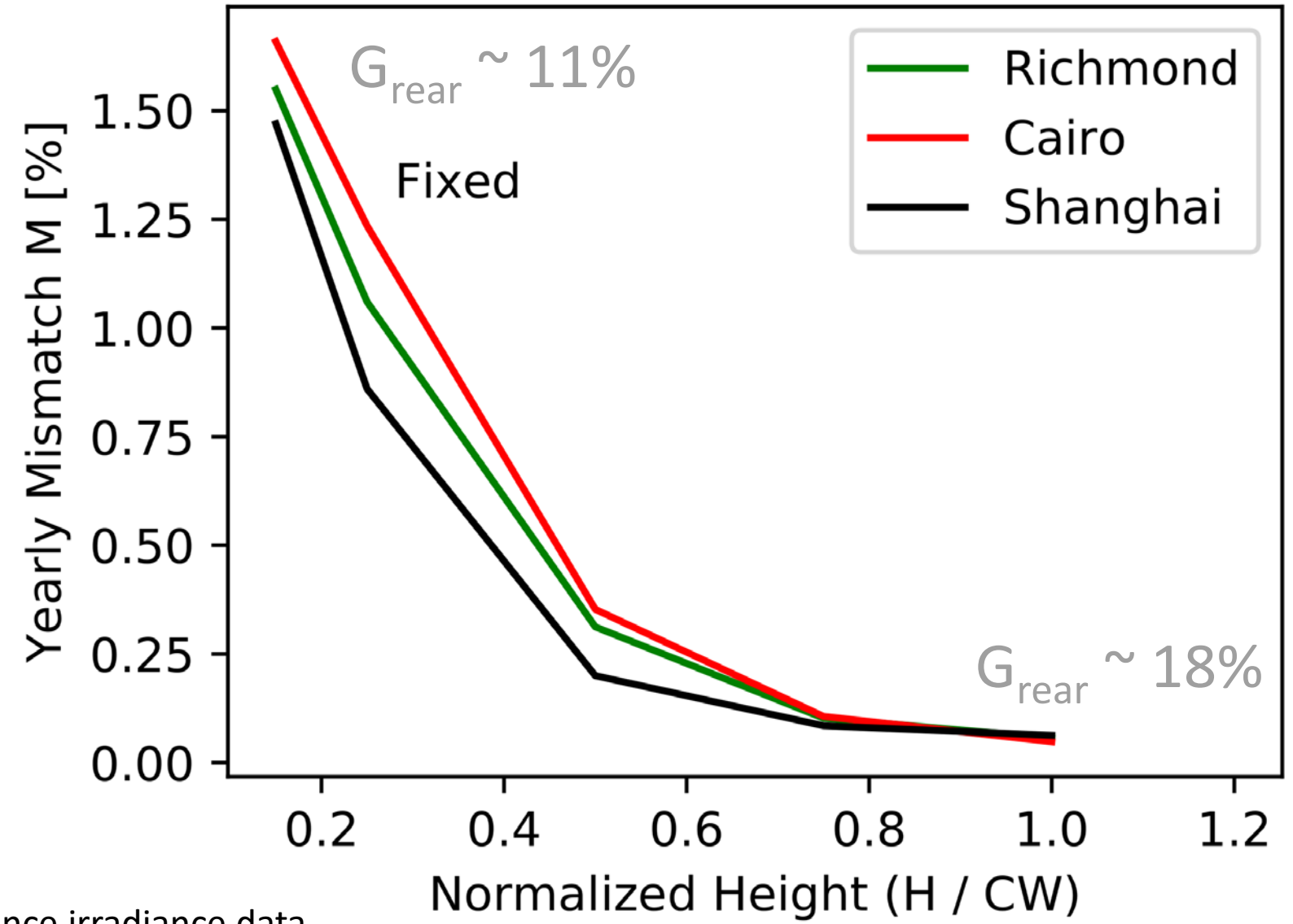
$$M = \left(1 - \frac{\sum_{h=0}^{8760} P_1}{\sum_{h=0}^{8760} P_0}\right) \times 100\%$$

PVMismatch, https://github.com/SunPower/PVMismatch
B. Marion, et al "Current--voltage curve translation by bilinear interpolation," PinPV 2004.
C. Olalla, D. Clement, D. Maksimovic, C. Deline "A Cell-level Photovoltaic Model for High-granularity Simulations", 15th EC PEC

Evaluating climate dependence

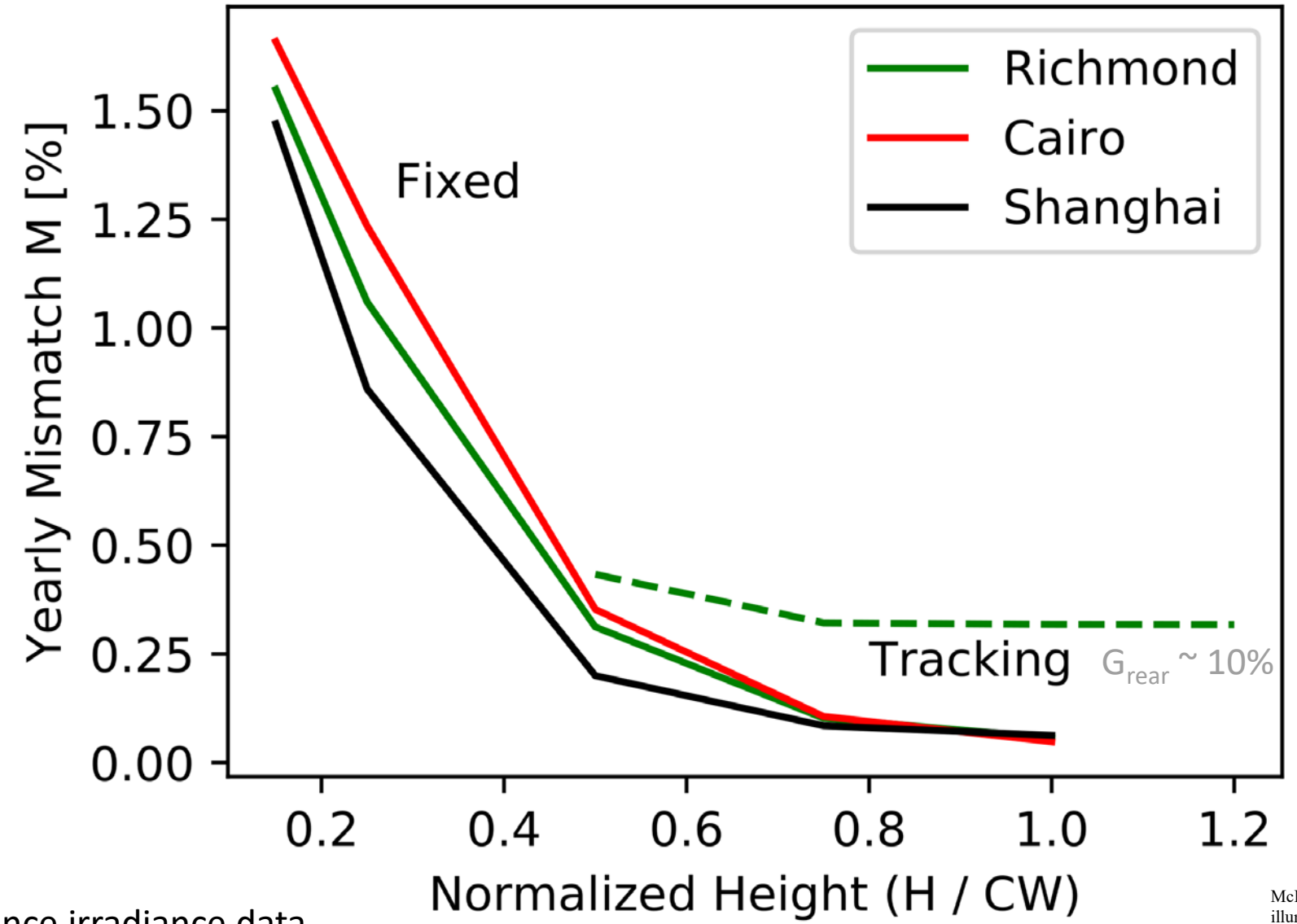


Slight climate dependence for high-albedo rooftop simulations



*bifacial_radiance irradiance data

HSAT Mismatch losses are slightly higher

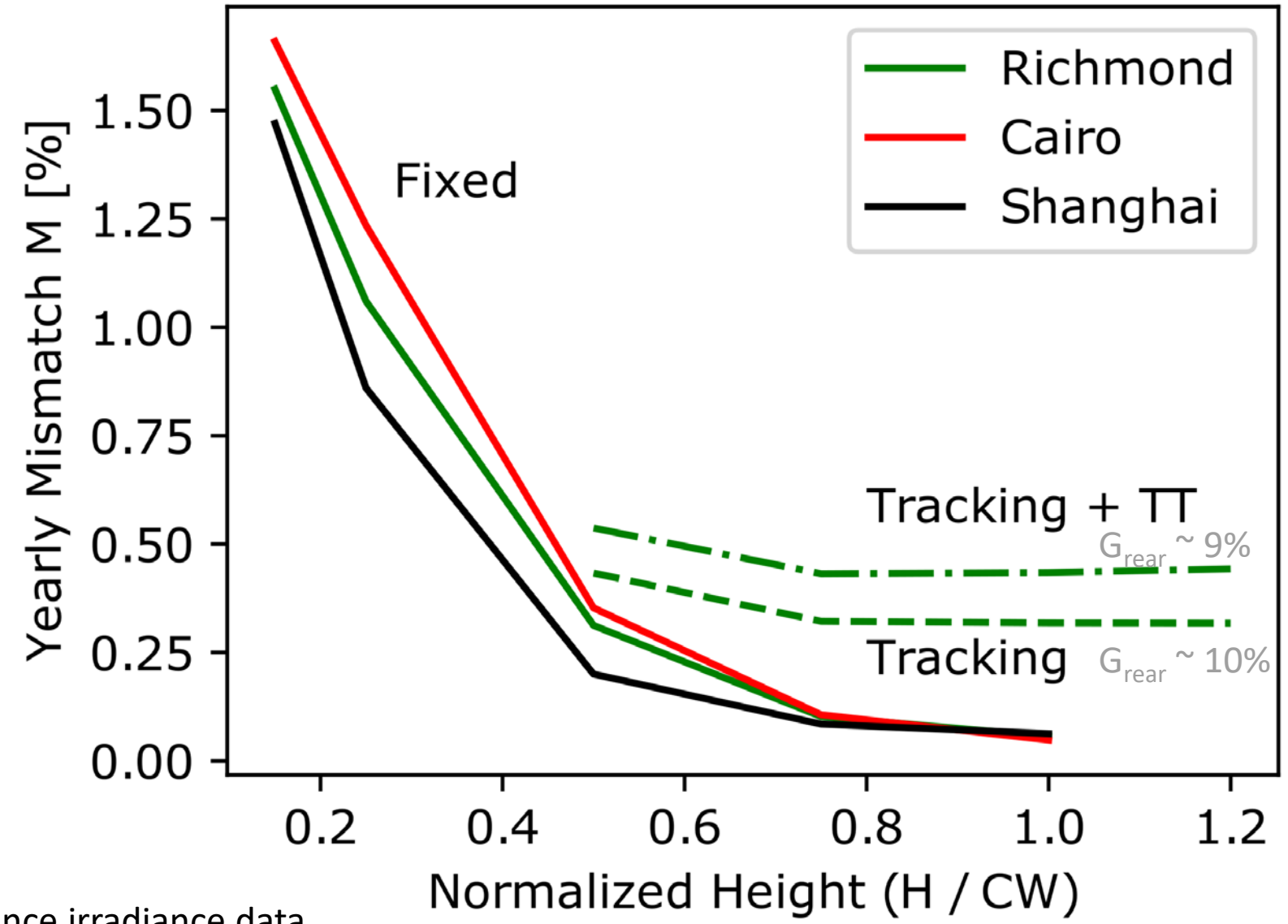


Annual mismatch loss is 0.3%–0.6%, matching the results of McIntosh et al (46th PVSC), which showed values of 0.3%–0.4% under similar conditions

*bifacial_radiance irradiance data

McIntosh KR, et al «Mismatch loss in bifacial modules due to non-uniform illumination in 1D tracking systems». 46th IEEE PVSC, Chicago, 2019

Torque tube increases mismatch by only 0.1%

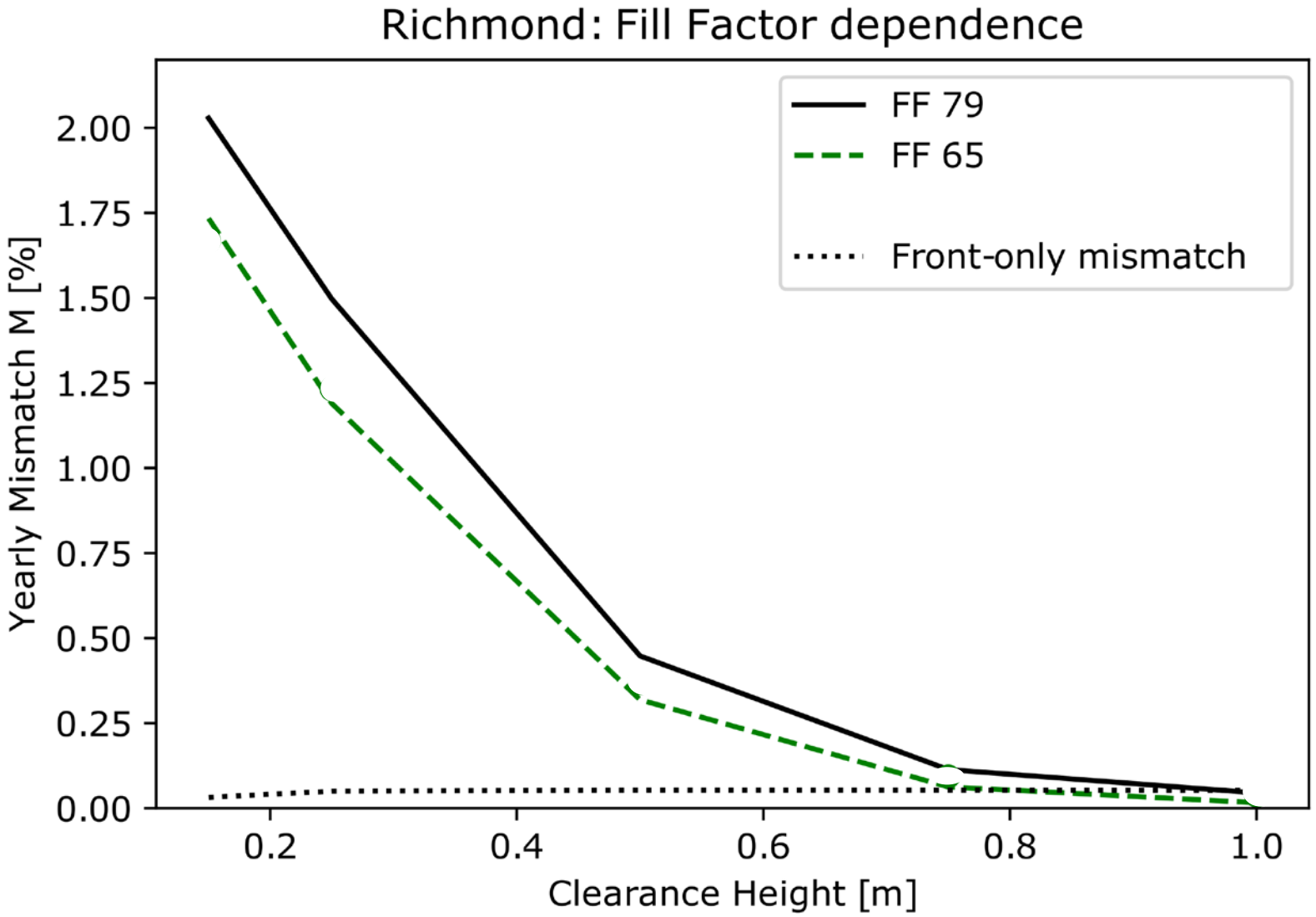


Torque tube:
10 cm diameter, 5 cm from the module (CW=2M), absorptive “black” material

*bifacial_radiance irradiance data

Fill Factor dependency

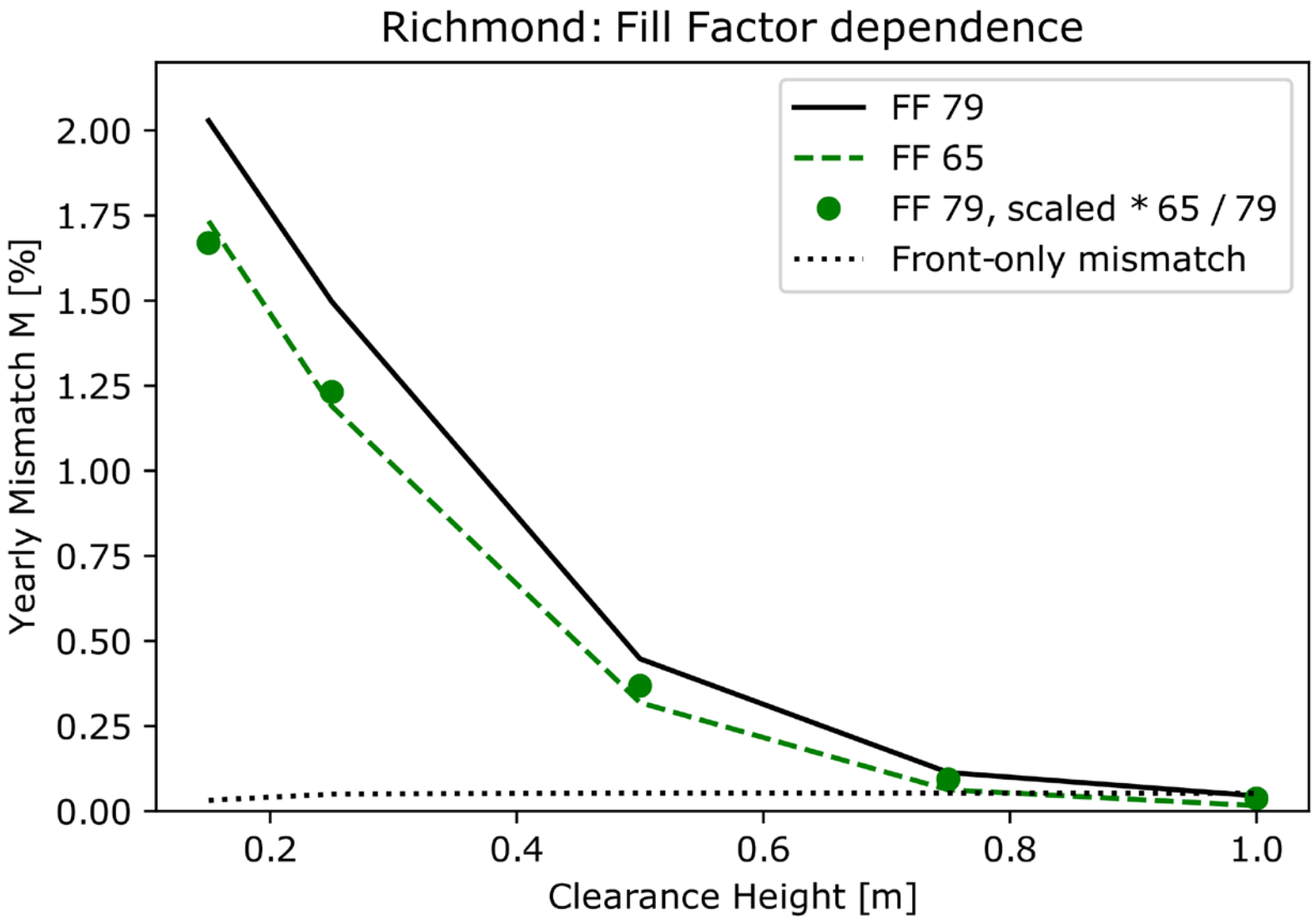
Lower Fill Factor modules are susceptible to reduced mismatch loss



*Fixed tilt cases shown with bifacialVF irradiance data

Fill Factor dependency

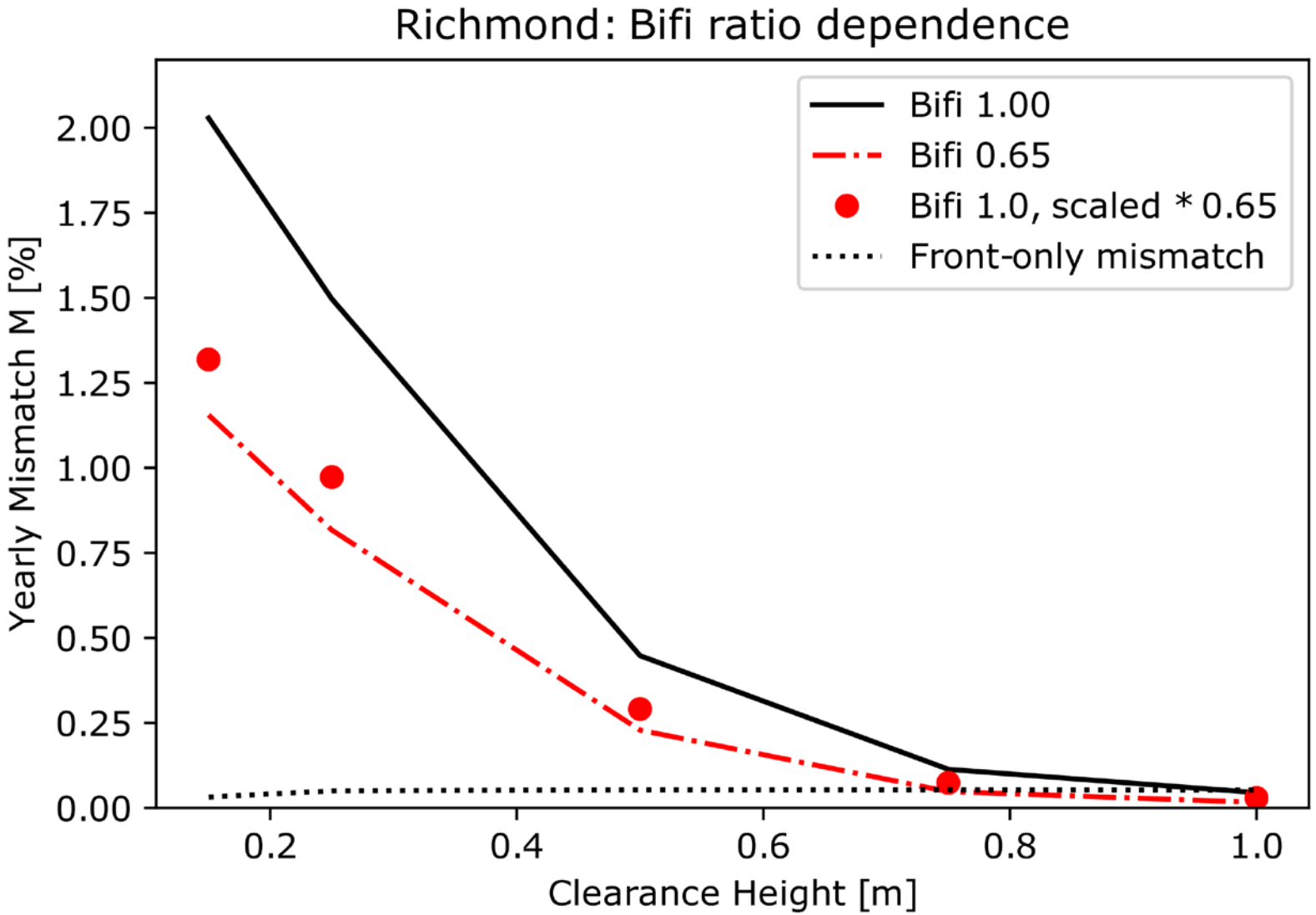
$$M[\%]_{FF1} = M[\%]_{FF_0} \frac{FF_1}{FF_0}$$



*Fixed tilt cases shown with bifacialVF irradiance data

Bifaciality Factor dependency

$$M[\%]_{\phi_{Bifi,1}} = M[\%]_{\phi_{Bifi,0}} \frac{\phi_{Bifi,1}}{\phi_{Bifi,0}}$$



*Fixed tilt cases shown with bifacialVF irradiance data

Reduced-order model

Reduced Order Model – Irradiance distribution

Mismatch depends on the total irradiance distribution.

Two statistical approaches:

Stdev

$$\sigma[\%] = \frac{1}{\bar{G}_{total}} \sqrt{\frac{\Sigma\left(G_{total,i} - \bar{G}_{total}\right)^2}{n-1}} \text{ x } 100\%$$

MAD Mean absolute difference

$$\Delta[\%] = \frac{1}{n^2 \bar{G}_{total}} \sum_{i=1}^{n} \sum_{j=1}^{n} \left| G_{total,i} - G_{total,j} \right| \text{ x } 100\%$$

$$G_{total} = G_{front} + \phi_{Bifi}\, G_{rear}$$

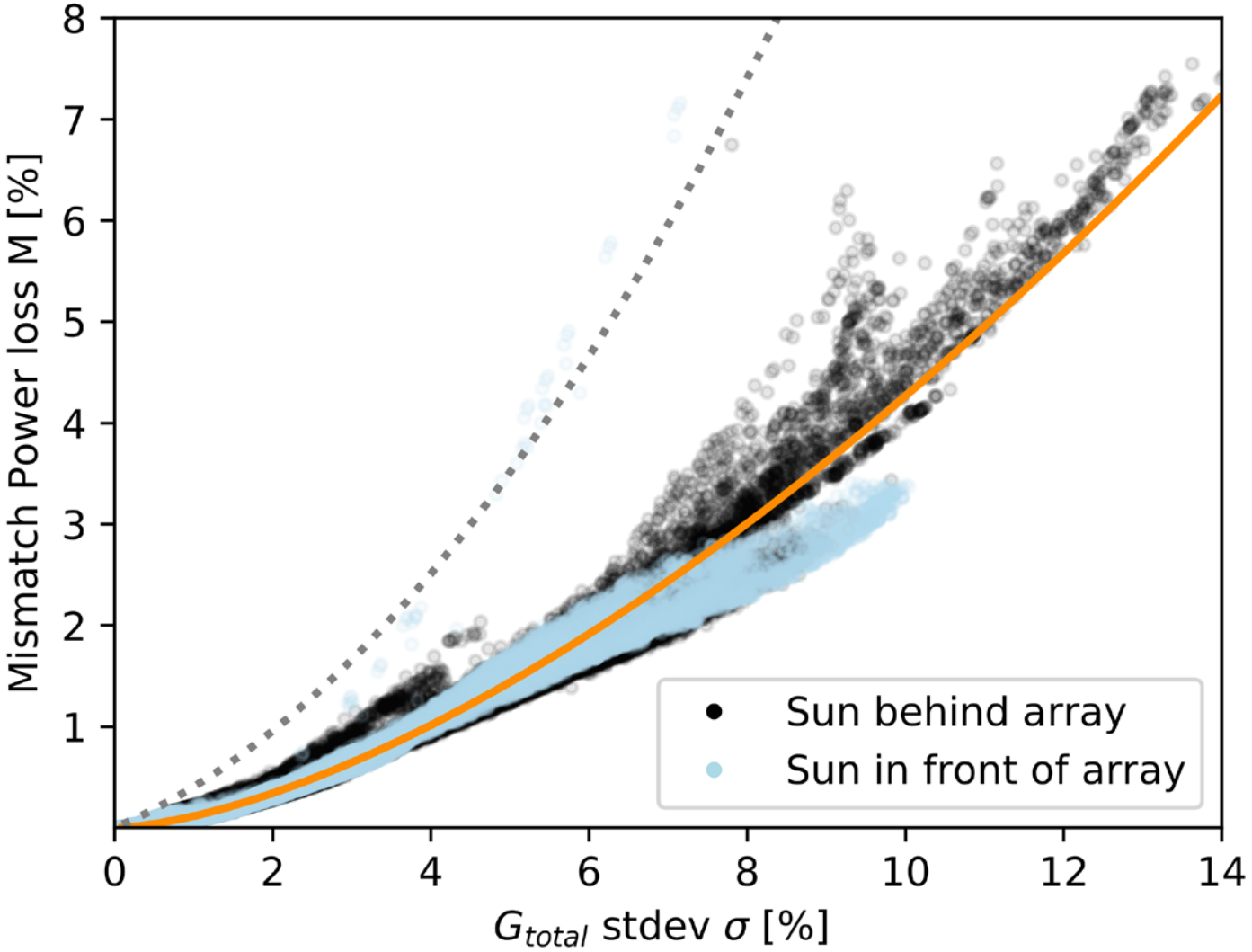
Reduced Order Model – fixed tilt

$$M[\%]_{Fit1} = \mathrm{e}^{\,1.57 * \ln(\sigma[\%]) - 2.2}$$

Janssen et al, «Impact of inhomogeneous irradiance at the rear of bifacial panels on modelled energy yield» 33rd EUPVSEC

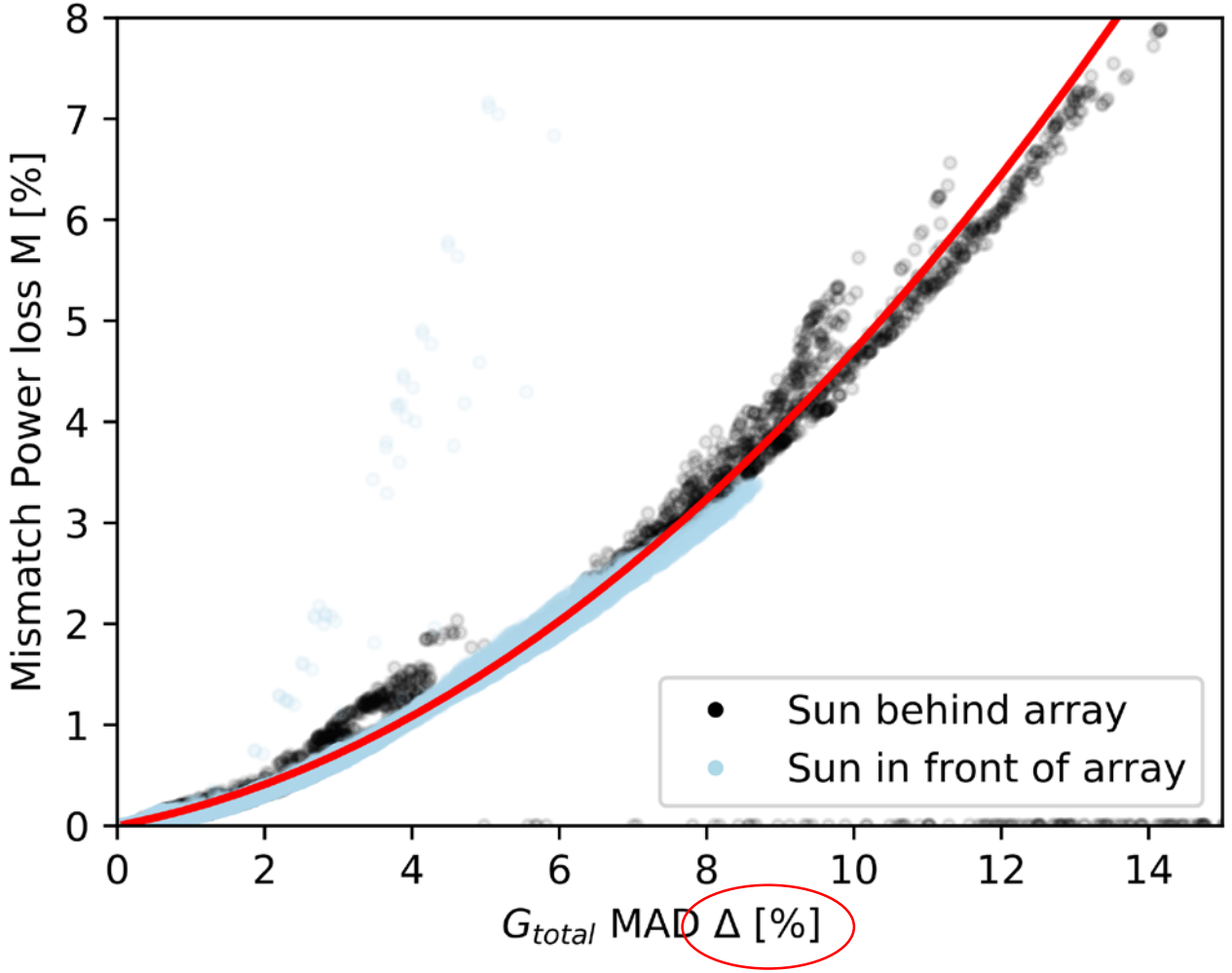
$$M[\%]_{\mathrm{Janssen}} = 0.33\,\sigma[\%] + 0.0745\,\sigma[\%]^2$$

$$G_{total} = G_{front} + \phi_{Bifi}\,G_{rear}$$



* Fixed tilt results – 130k datapoints

Reduced Order Model: MADs fixed tilt



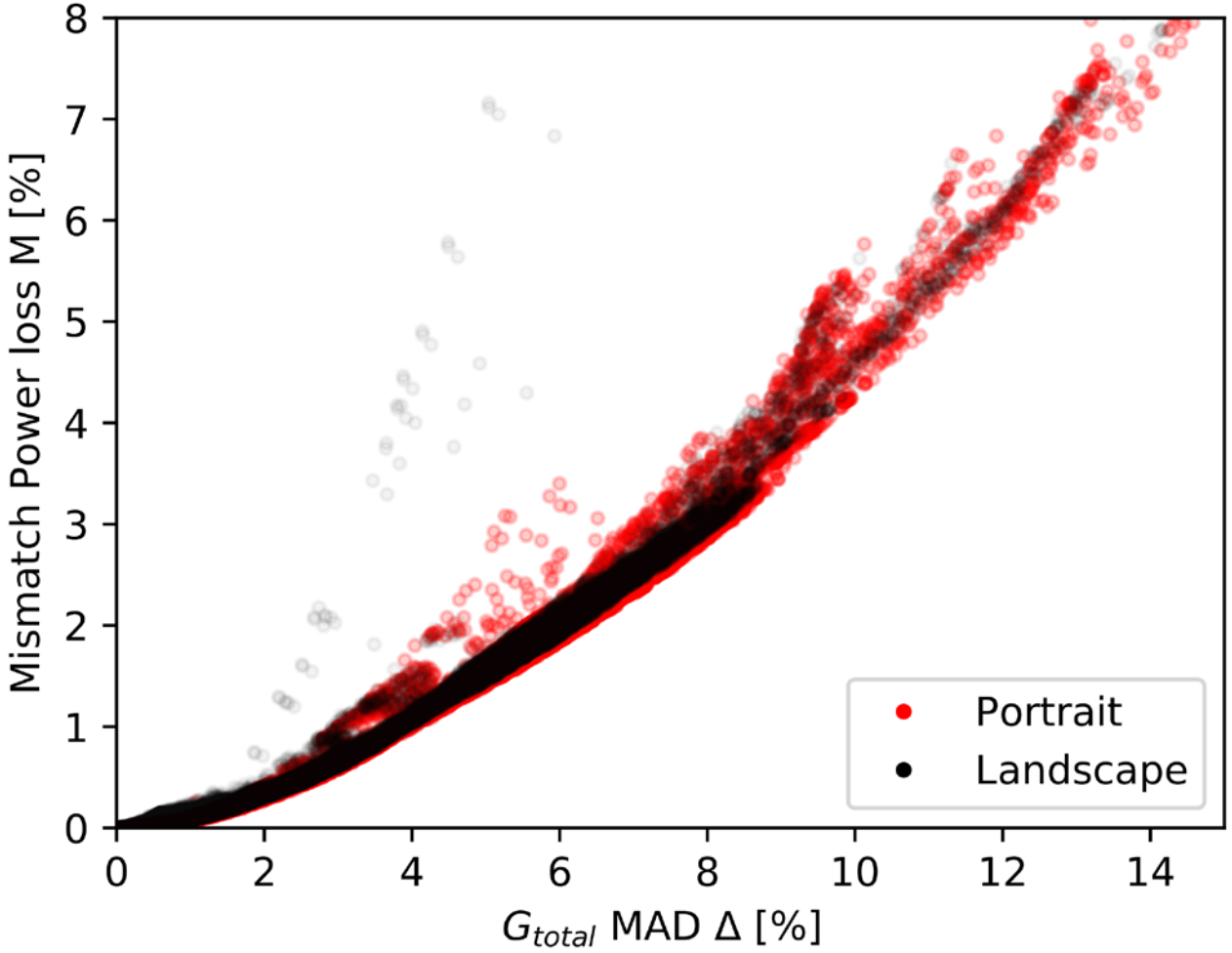
*Tighter distribution by using Δ instead of σ

$$M[\%]_{Fit2} = 0.142\,\Delta[\%] + 0.032\,\Delta[\%]^2$$

$$\Delta = Mean\ Absolute\ Difference\ (G_{total})$$

$$G_{total} = G_{front} + \phi_{Bifi}\,G_{rear}$$

Orientation of the module



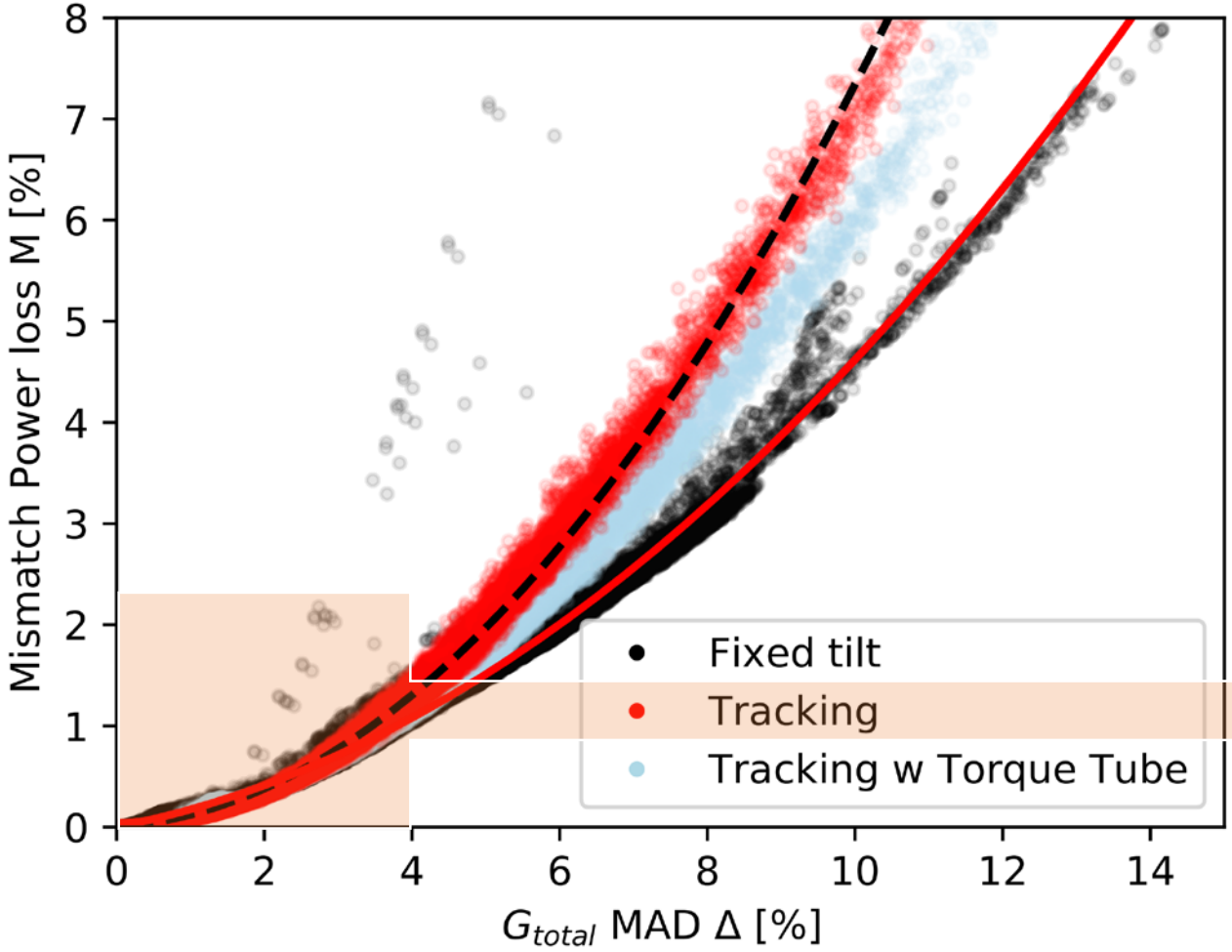
*No effect from landscape vs portrait orientation

$$\Delta = Mean\ Absolute\ Difference\ (G_{total})$$

$$G_{total} = G_{front} + \phi_{Bifi}\, G_{rear}$$

* With Tracking, ~90k datapoints

Tracking & Fixed Tilt



agreement is much better at $\Delta < 4$, where bulk of the energy is at.

$$\Delta = Mean\ Absolute\ Difference\ (G_{total})$$

$$G_{total} = G_{front} + \phi_{Bifi}\, G_{rear}$$

* With Tracking, ~90k datapoints

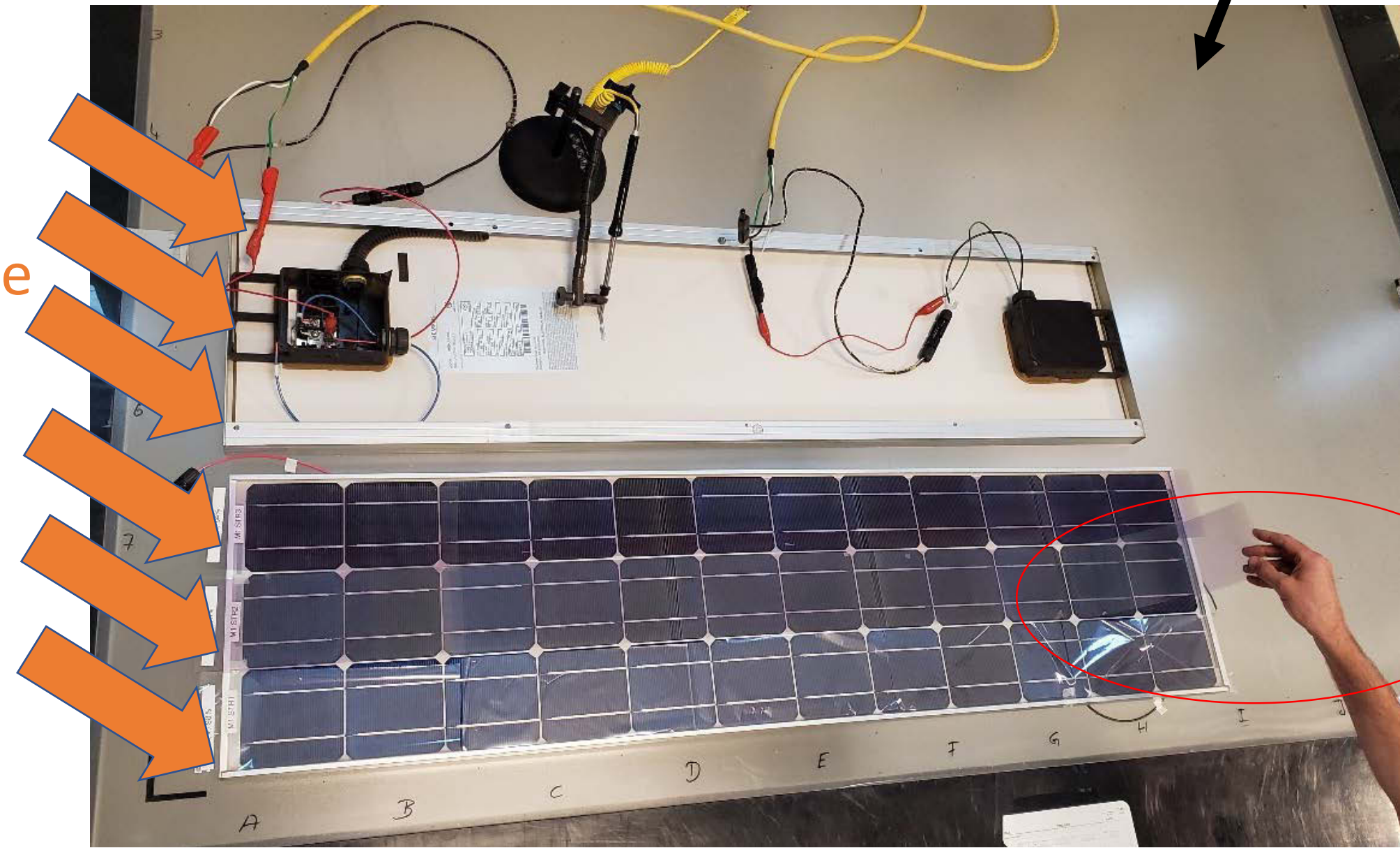
Reduced-order model

? EXPERIMENTAL VALIDATION

Experimental Validation

Spire 4600 long-pulse flash I-V curve simulator.

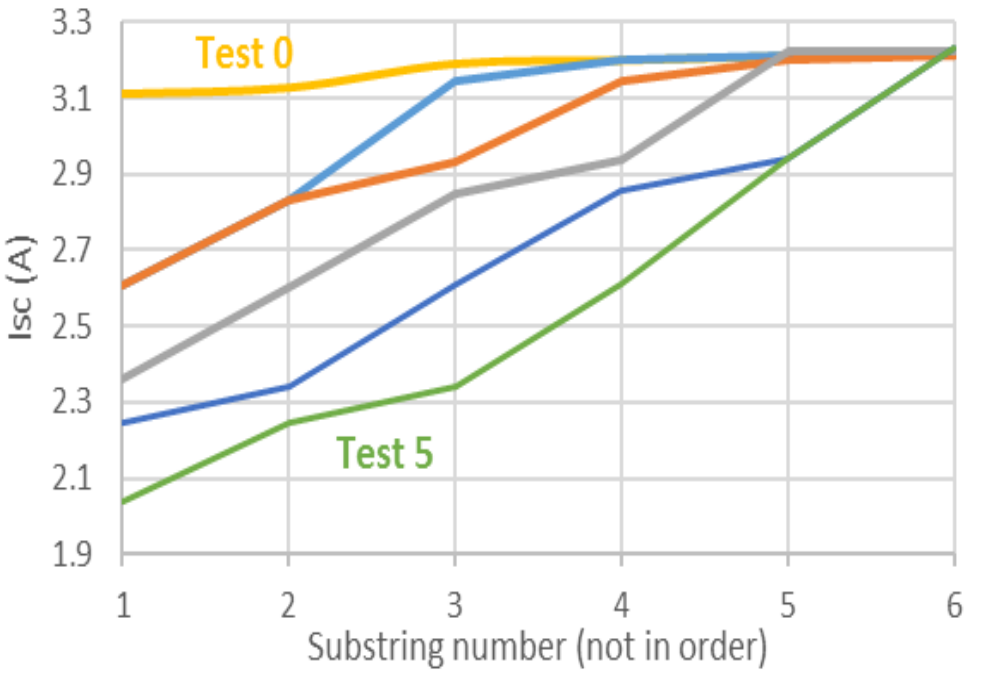
6 addressable cell sub-strings



Tests

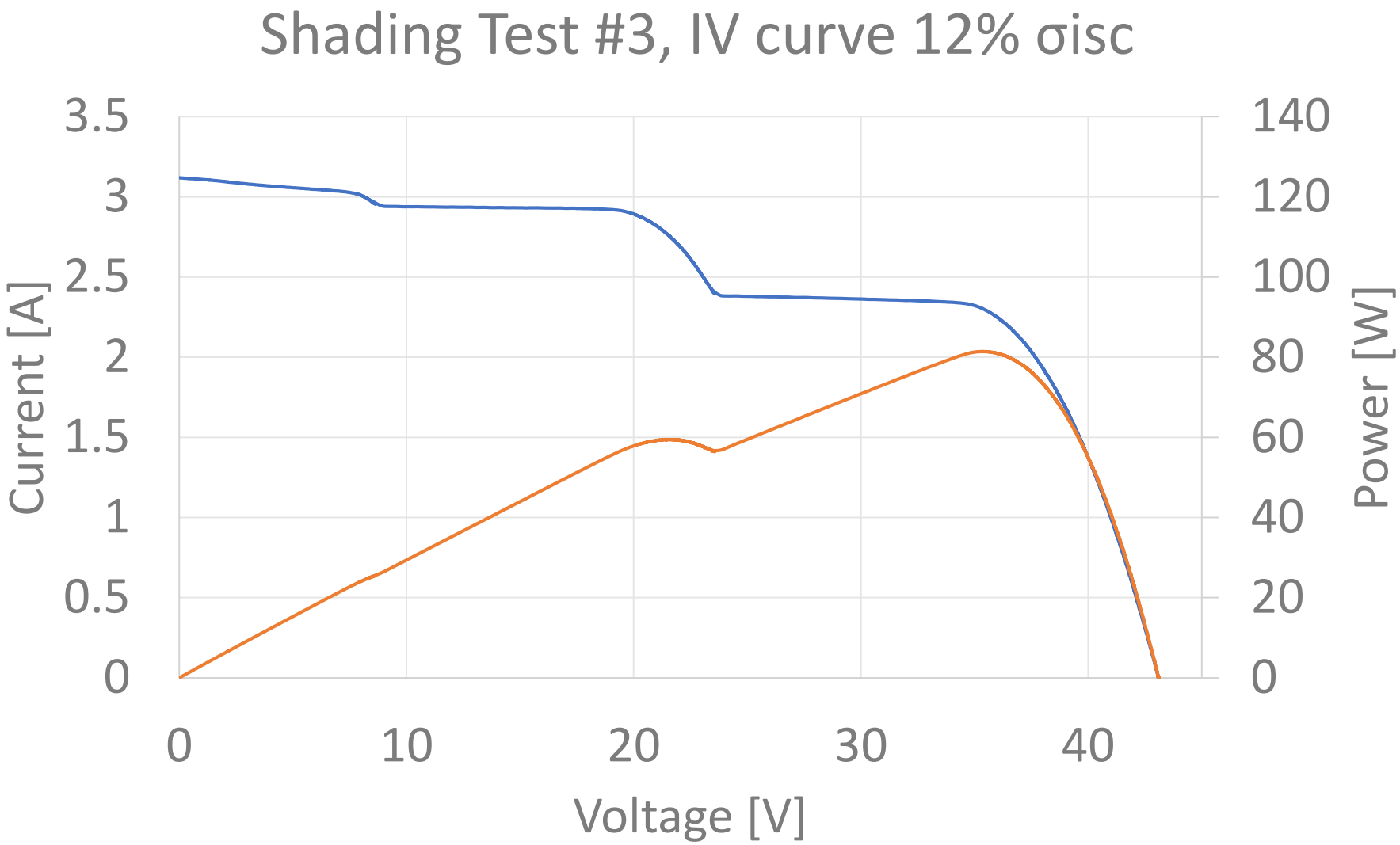
Test#	M1 str1 (%)	M1 str2 (%)	M1 str3 (%)	M2 str1 (%)	M2 str2 (%)	M2 str3 (%)
0	-	-	-	-	-	-
1	90	-	84	-	-	-
2	90	-	84	-	-	90
3	90	7	84	-	-	90
4	90	75	84	70	-	90
5	64	75	84	70	-	90

Measured substring I_{sc} for each of the shading tests

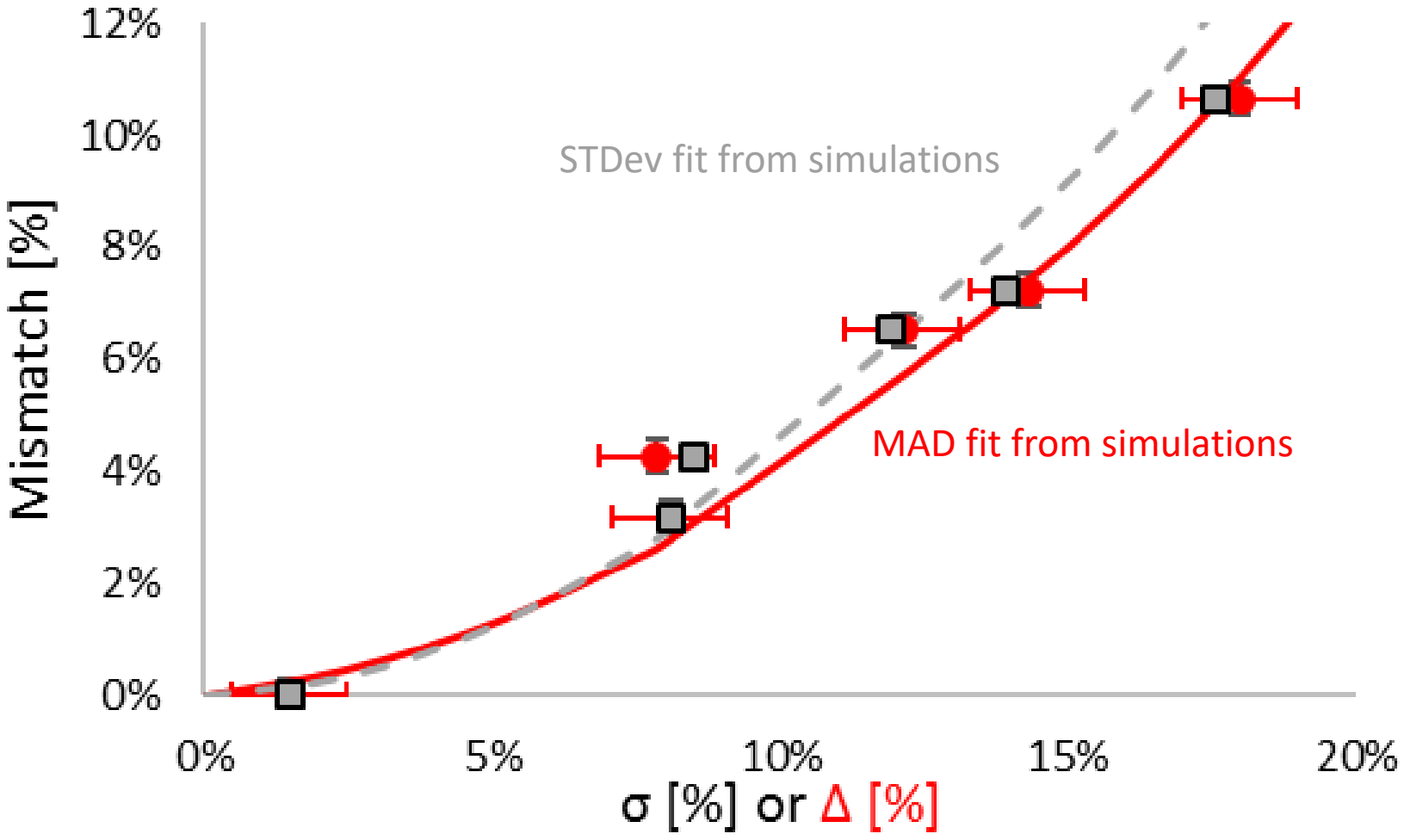


I_{sc} STD & MAD each vary from 1.5% - 18%

I-V curve measurements

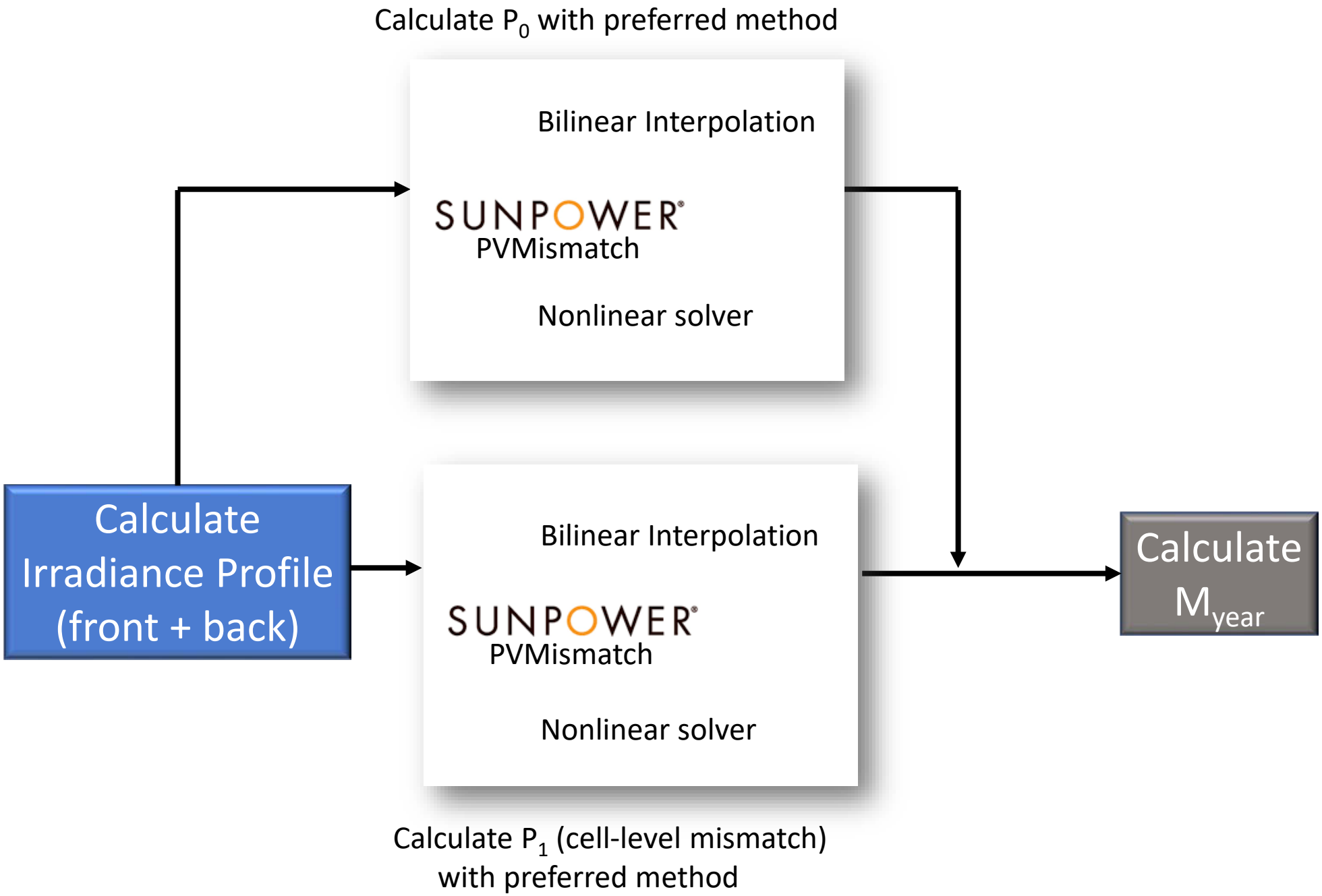


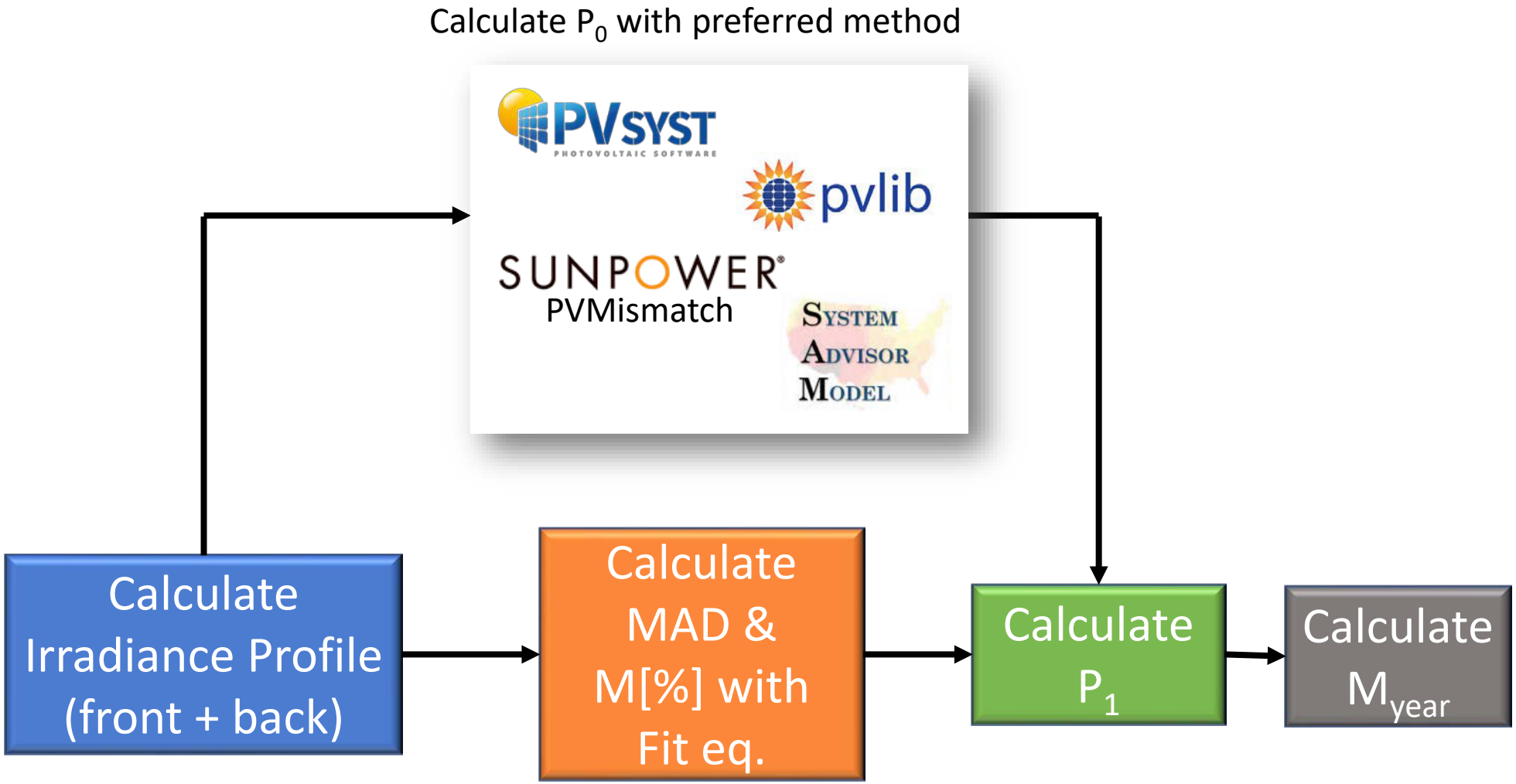
Measured mismatch loss



Reduced-order model

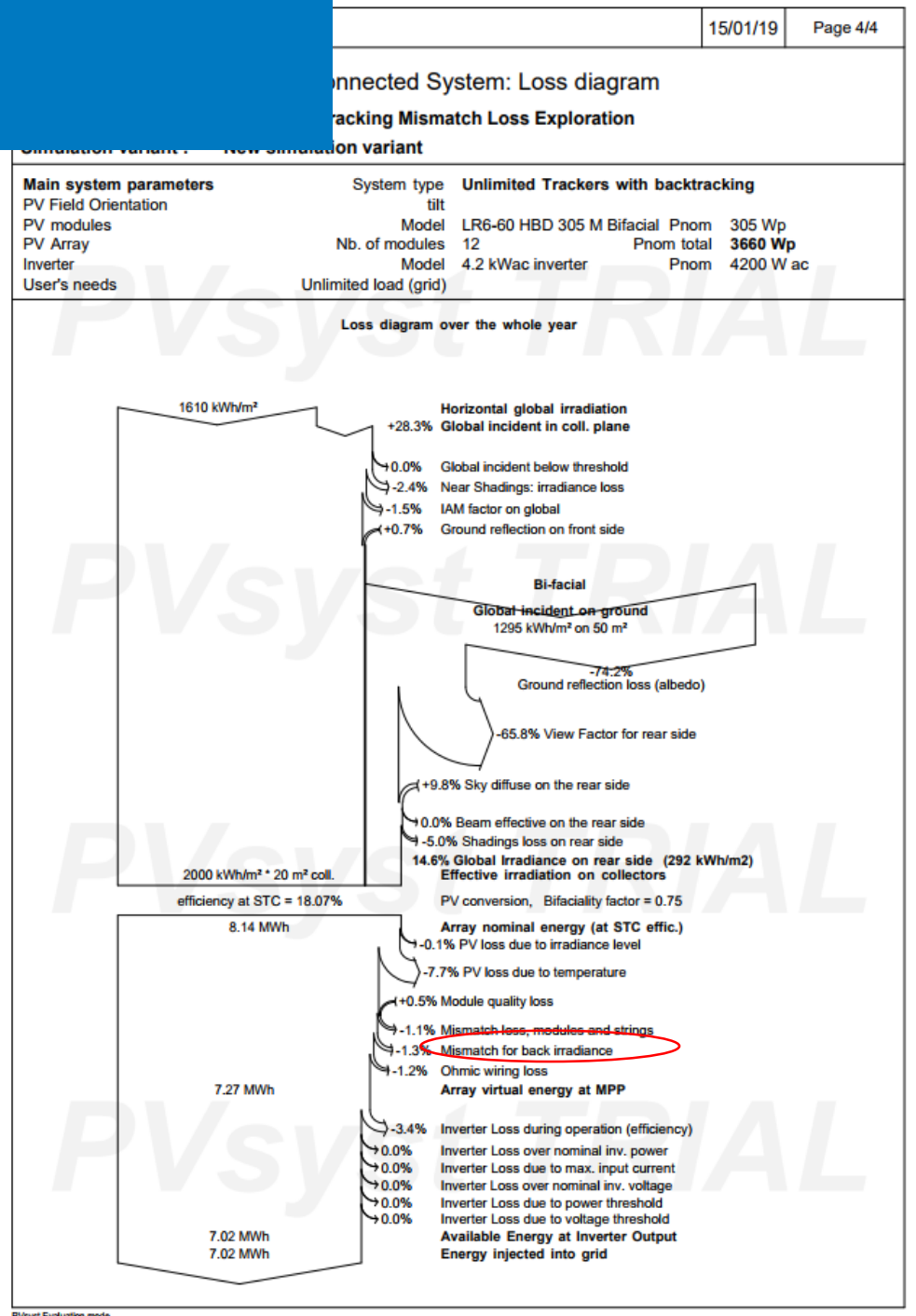
EXPERIMENTAL VALIDATION


Calculate P_0 with preferred method
Bilinear Interpolation
SUNPOWER
PVMismatch
Nonlinear solver
Calculate Irradiance Profile (front + back)
Bilinear Interpolation
SUNPOWER
PVMismatch
Nonlinear solver
Calculate M_{year}
Calculate P_1 (cell-level mismatch) with preferred method


Calculate P_0 with preferred method
PVSYST
PHOTOVOLTAIC SOFTWARE
pvlib
SUNPOWER
PVMismatch
SYSTEM ADVISOR MODEL
Calculate Irradiance Profile (front + back)
Calculate MAD & M[%] with Fit eq.
Calculate P_1
Calculate M_{year}

How to use this M parameter?

- Mismatch loss factor a.k.a. rear mismatch loss, affects the Mismatch for back irradiance in the loss diagram



15/01/19 Page 4/4

nnected System: Loss diagram

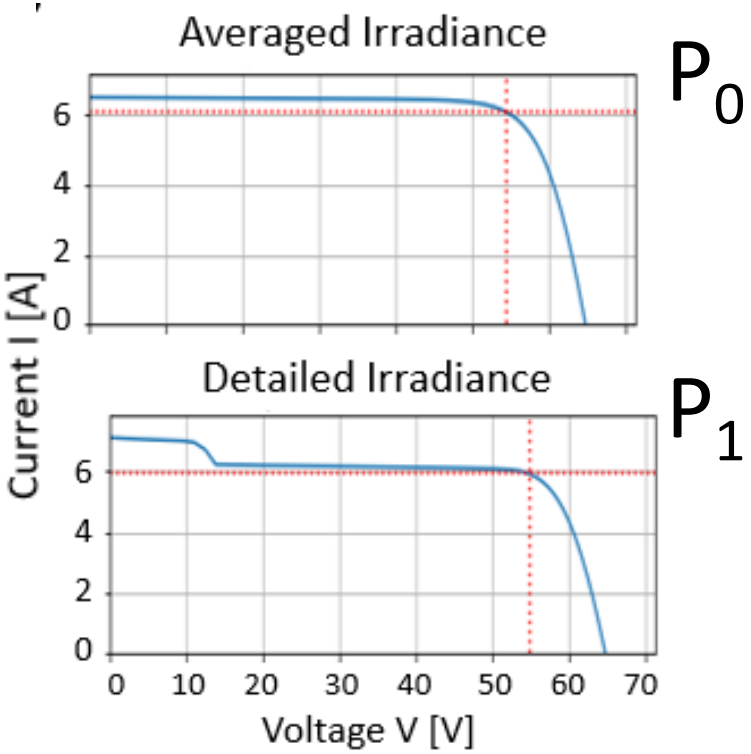
racking Mismatch Loss Exploration

on variant

Main system parameters	System type	**Unlimited Trackers with backtracking**		
PV Field Orientation	tilt			
PV modules	Model	LR6-60 HBD 305 M Bifacial	Pnom	305 Wp
PV Array	Nb. of modules	12	Pnom total	**3660 Wp**
Inverter	Model	4.2 kWac inverter	Pnom	4200 W ac
User's needs	Unlimited load (grid)			

Loss diagram over the whole year

Shading Factor and Rear Electrical Mismatch Factors



P_0

P_1

$$P_0 = \left(G_{F_0} + G_{R_0} \cdot \varphi\right) \cdot \eta_0$$

$$P_1 = \left(G_{F_0} + G_{R_0} \cdot \varphi\right) \cdot \eta_0 \cdot (1 - M)$$

1%

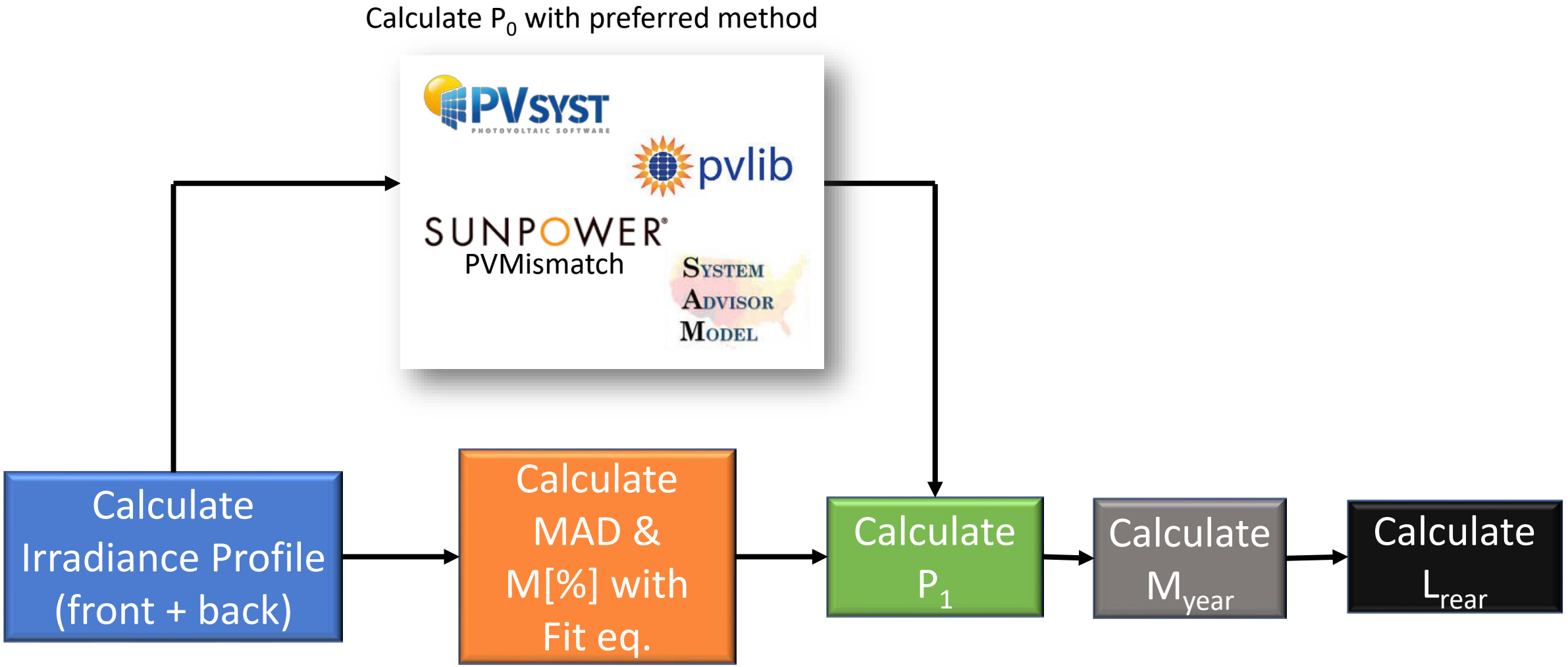
$$P_1 = \left(G_{F_0} + (1 - L_{Rear}) G_{R_0} \cdot \varphi\right) \cdot \eta_0$$

$$L_{Rear} = L_{Inherent\ Mismatch} + L_{Structural\ Shading}$$

11%

$$L_{Rear} = \frac{M}{BG} + M$$

10%

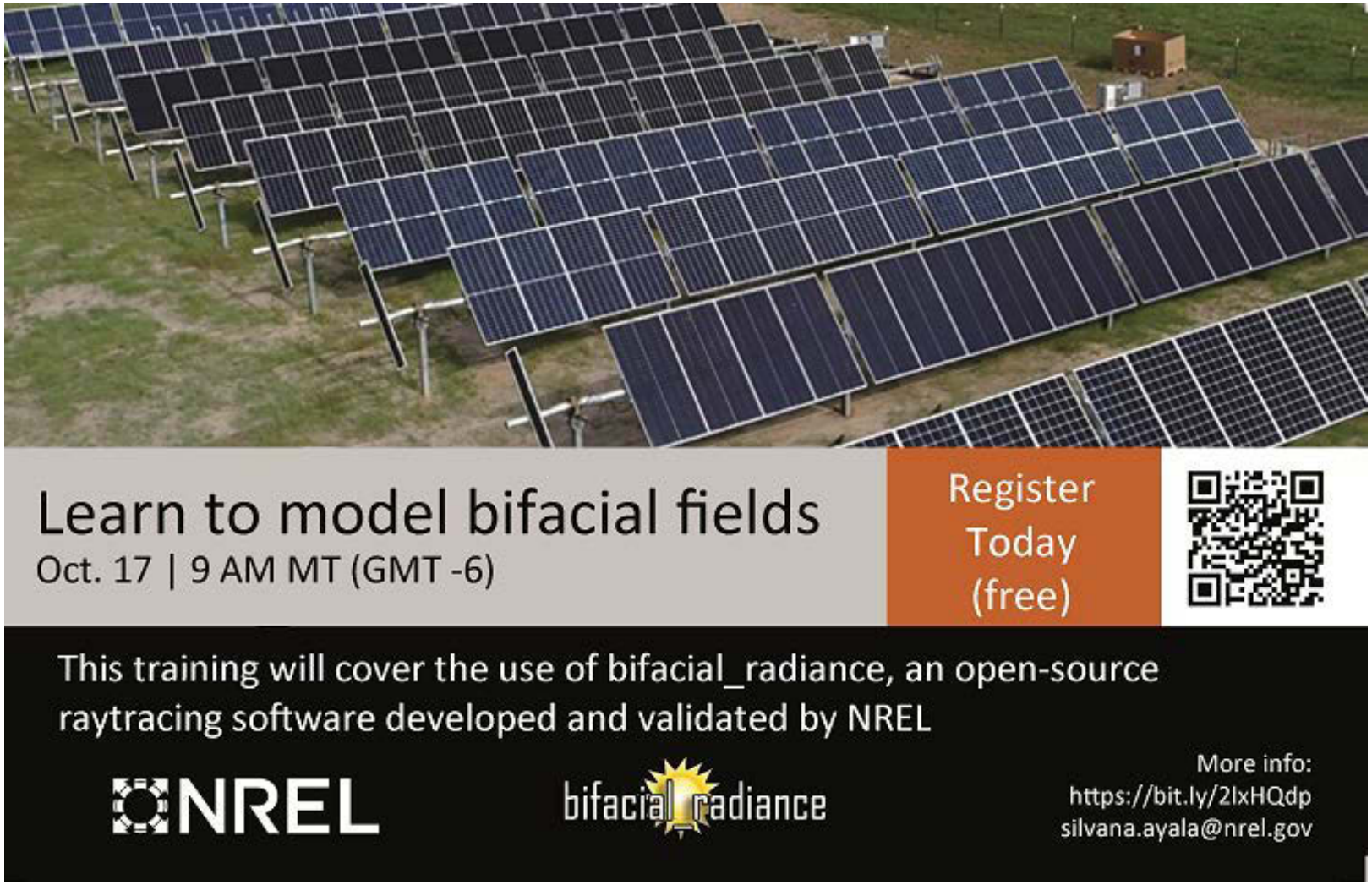

Calculate P_0 with preferred method
PVSYST
PHOTOVOLTAIC SOFTWARE
pvlib
SUNPOWER
PVMismatch
SYSTEM ADVISOR MODEL
Calculate Irradiance Profile (front + back)
Calculate MAD & M[%] with Fit eq.
Calculate P_1
Calculate M_{year}
Calculate L_{rear}

Conclusions

- Optical and cell-mismatch simulations were conducted on NREL's HPC to approximate bifacial fixed-tilt and tracking configurations in 3 climate zones.
- Annual mismatch loss was $M \leq 1\%$ for most configurations.
- For use in due diligence softwares, the value must be corrected by ~10x to apply only to $G_{rear.}$
- Hourly values of M[%] can be much higher and follow an empirical relationship vs G_{Total} mean absolute difference Δ (spatial variation).
- Experiments with artificially applied mismatch confirm the empirical relationship, and adjustments for module *FF* and ϕ_{Bifi} are described.

*C. Deline, S. Ayala Pelaez, S. MacAlpine, C. Olalla "Estimating and Parameterizing Mismatch Power Loss in Bifacial Photovoltaic Systems", (*submitted*)

Slides to be open-published on NREL's database, link posted on:
https://github.com/NREL/bifacial_radiance/wiki



Thank you

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