Better understanding and fitting of IV curves and IEC 61853 matrix measurements

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IOP, London….

Why do we need to understand IV curves and efficiency matrices versus Irradiance and Module Temperature ?

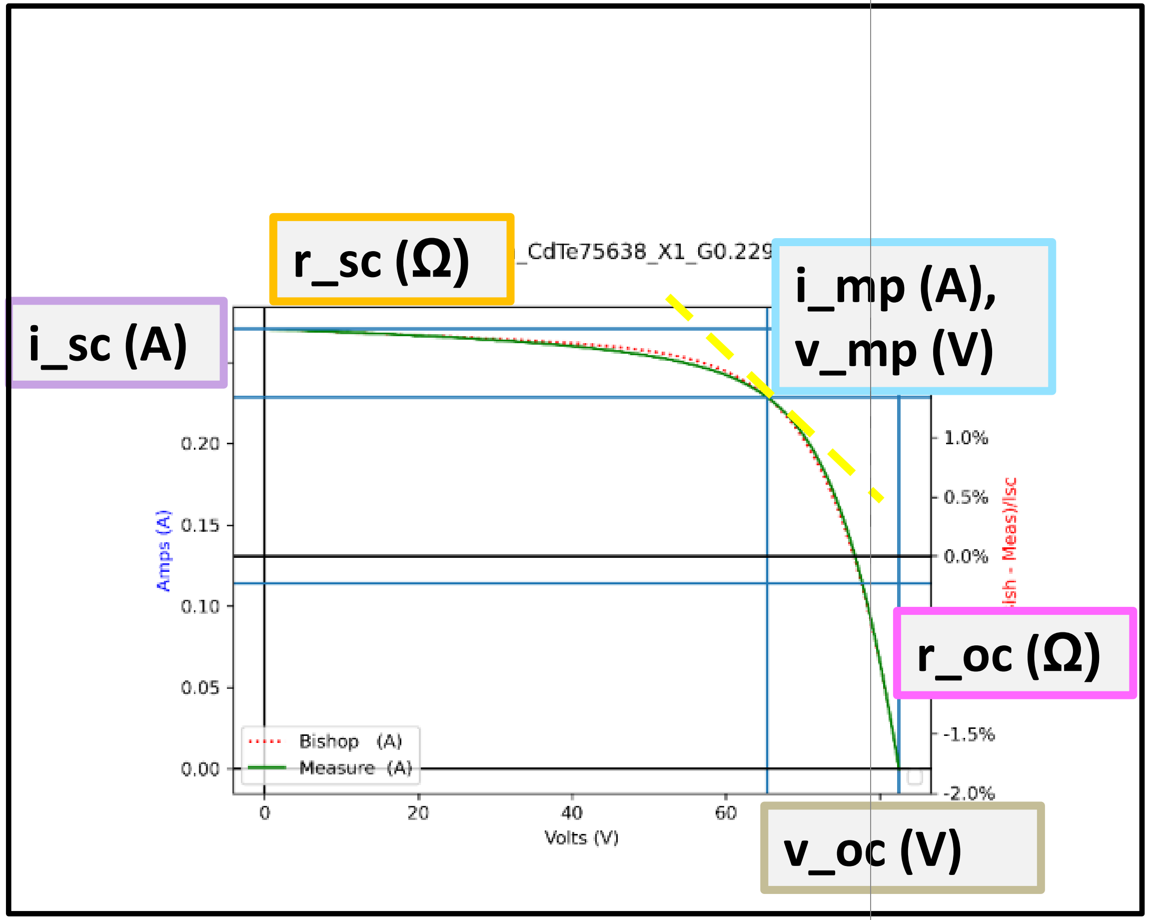
Instantaneous power depends on the weather
p_mp (W) = fn(Irradiance G, Module Temperature T, Angle of incidence, Spectrum) also soiling, ageing etc..

- Measure vs. a range or matrix of **G** and **T** then fit a model **p_mp** (**G**, **T**)
- Calculate energy yield **YA**(kWh/kWp)
  $\sim \Sigma_{time}$ **p_mp**(**G_{time}**, **T_{time}**) / kWp (e.g. over a year's climate)
- Check predicted vs. measured **p_mp** for degradation and/or faults

Typical IV curve and derived parameters

1-diode model

$$I = I_L - I_0\left(\exp\left(\frac{V + IR_s}{nNsV_{th}}\right) - 1\right) - \frac{V + IR_s}{R_{sh}}$$



Calculated gradient

$$\left(\frac{d(I * V)}{dV}_{@V=v\_mp}\right) = 0$$

Typical IV curve and derived parameters

1-diode model

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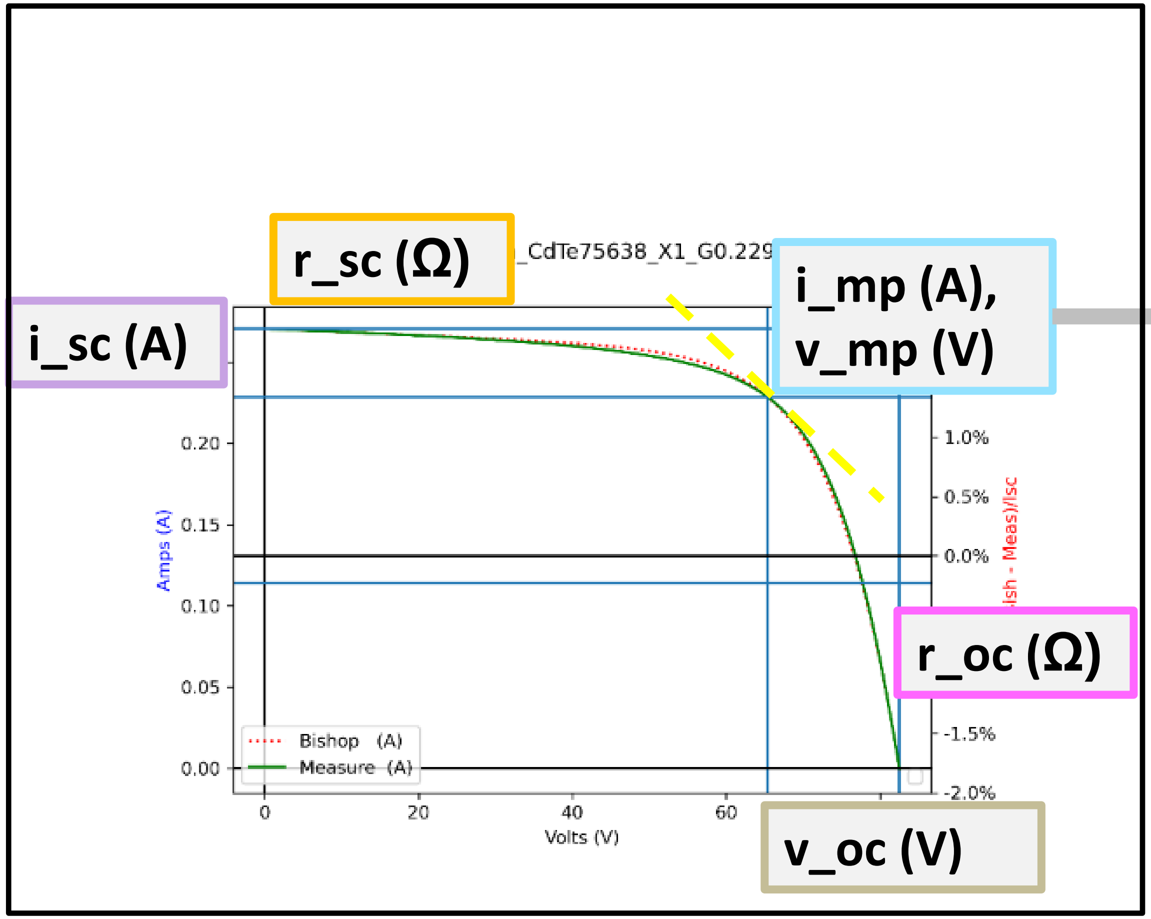


calculations

p_mp (W),
fill factor (%),

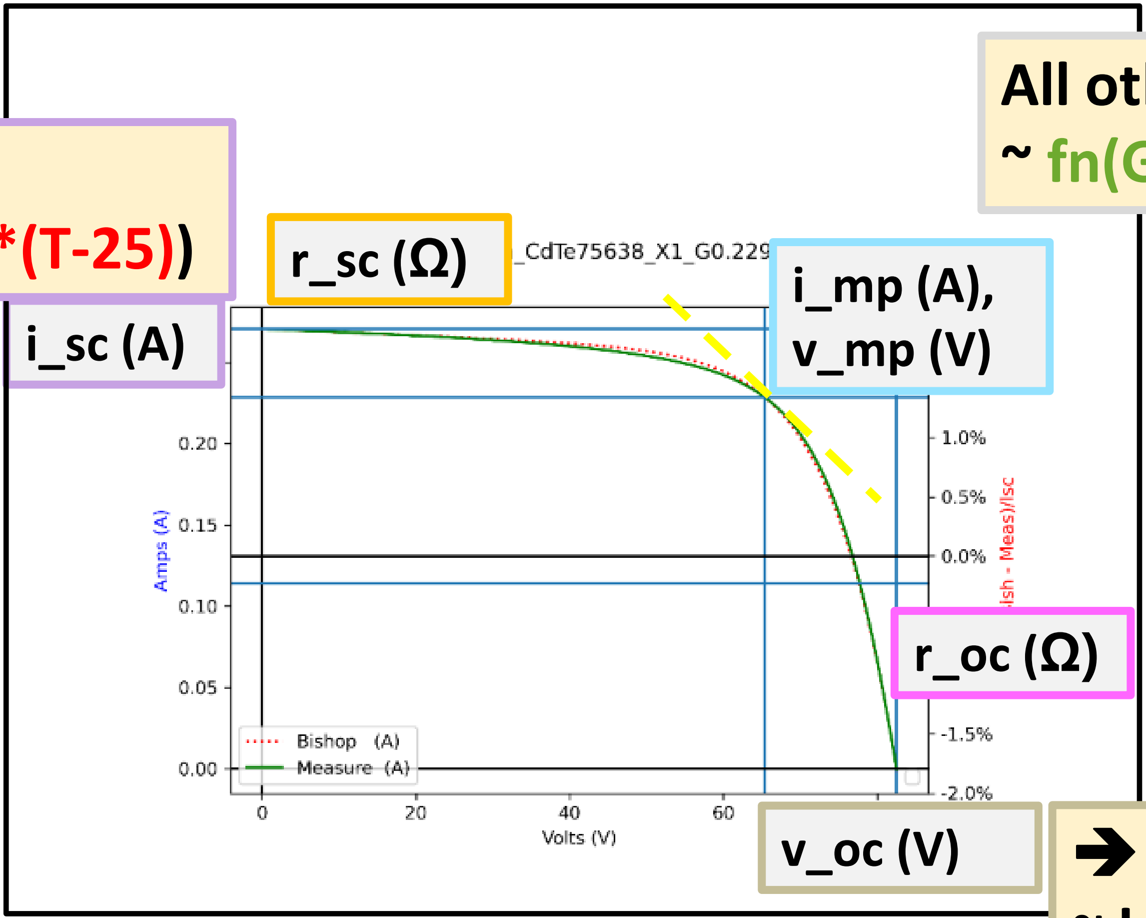
STC values.
Area m²

Efficiency (%),
PR_DC (%)

How do these parameters depend on weather values?

1 diode model

$$I = I_L - I_0\left(\exp\left(\frac{V+IR_s}{nNsV_{th}}\right)-1\right) - \frac{V+IR_s}{R_{sh}}$$



↑ i_sc
~ G * (1+α_isc*(T-25))

i_sc (A)

r_sc (Ω)

i_mp (A),
v_mp (V)

All other params
~ fn(G) * fn(T)

r_oc (Ω)

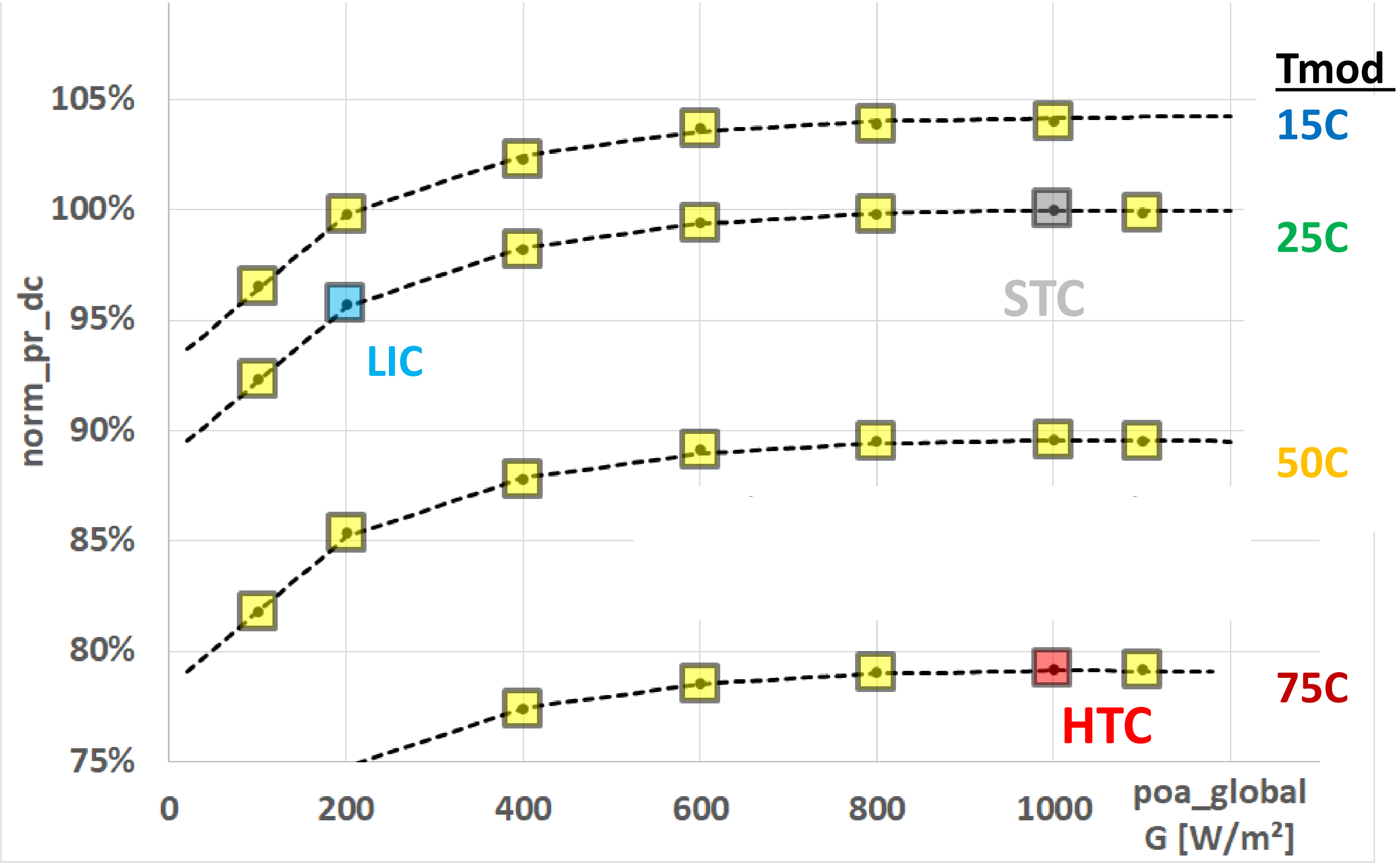
v_oc (V)

➔ v_oc
~ log(G)*(1+β_voc*(T-25))

Typical relative efficiency matrix = PRdc(G,T)

(c-Si) as on datasheets, PVSyst etc.

$$pr\_dc = \frac{meas\_eff}{stc\_eff} = \frac{meas\_p\_max}{stc\_p\_max} * \frac{1}{g\_kW/m^2}$$

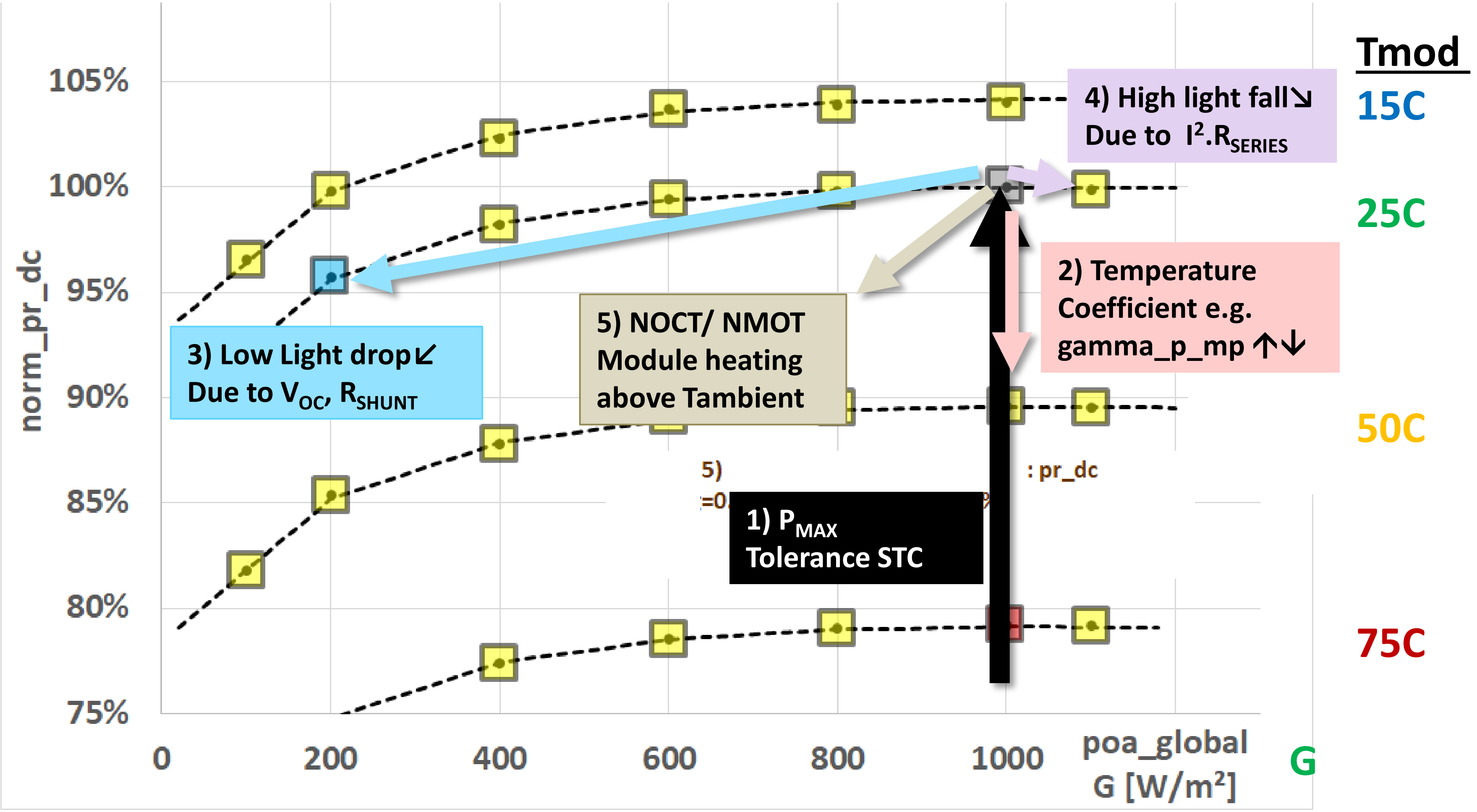


Typical relative efficiency matrix = PRdc(G,T)

(c-Si) as on datasheets, PVSyst etc.

```
pr_dc = meas_eff = meas_p_max        * 1
        stc_eff    stc_p_max * g_kW/m²
```

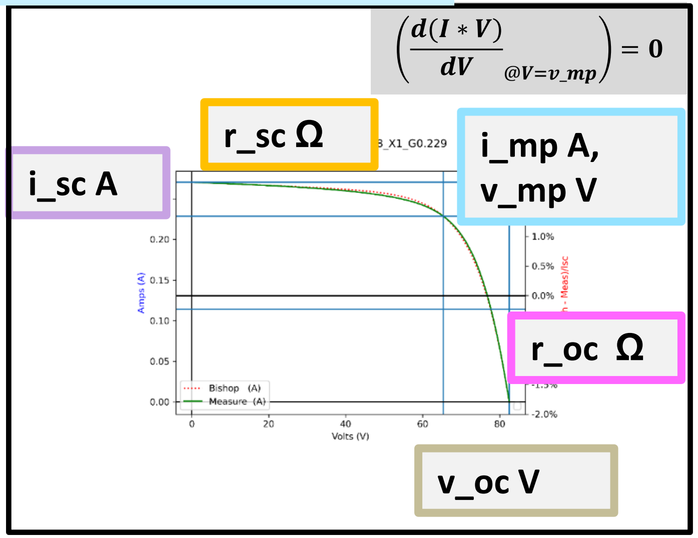
Shape of PRdc(G, T) is dominated by these five separate effects

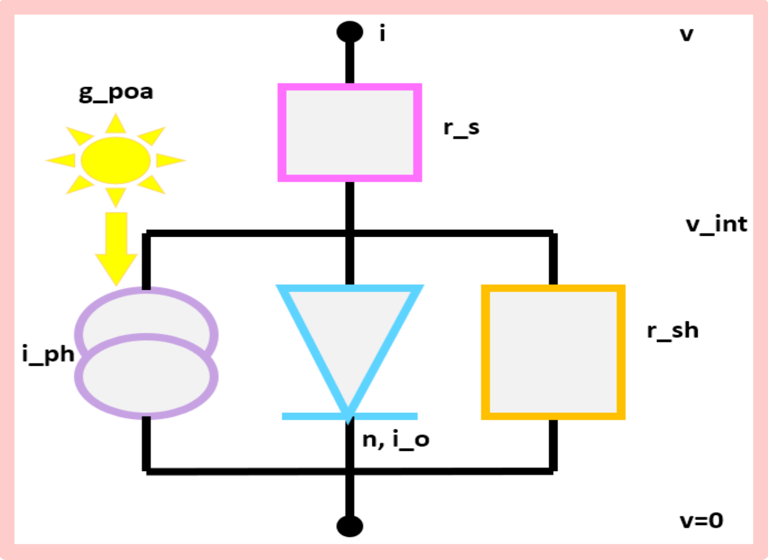


IV curve fit → 1 diode and MLFM* (*mechanistic loss factors model)

colours show which component 'dominates' each fit parameter

Measured IV curve



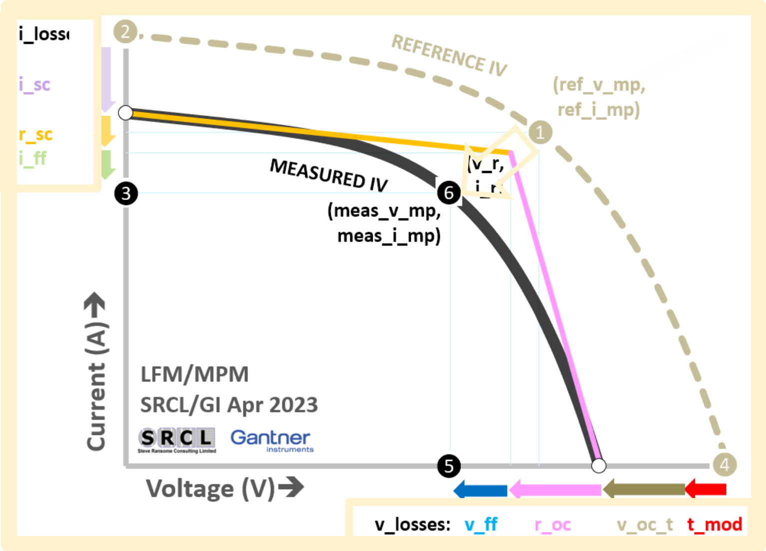


$$I = I_L - I_0\left(\exp\left(\frac{V + IR_s}{nNsV_{th}}\right) - 1\right) - \frac{V + IR_s}{R_{sh}}$$

Fit to 1-diode model

best fits to IV curves are limited by

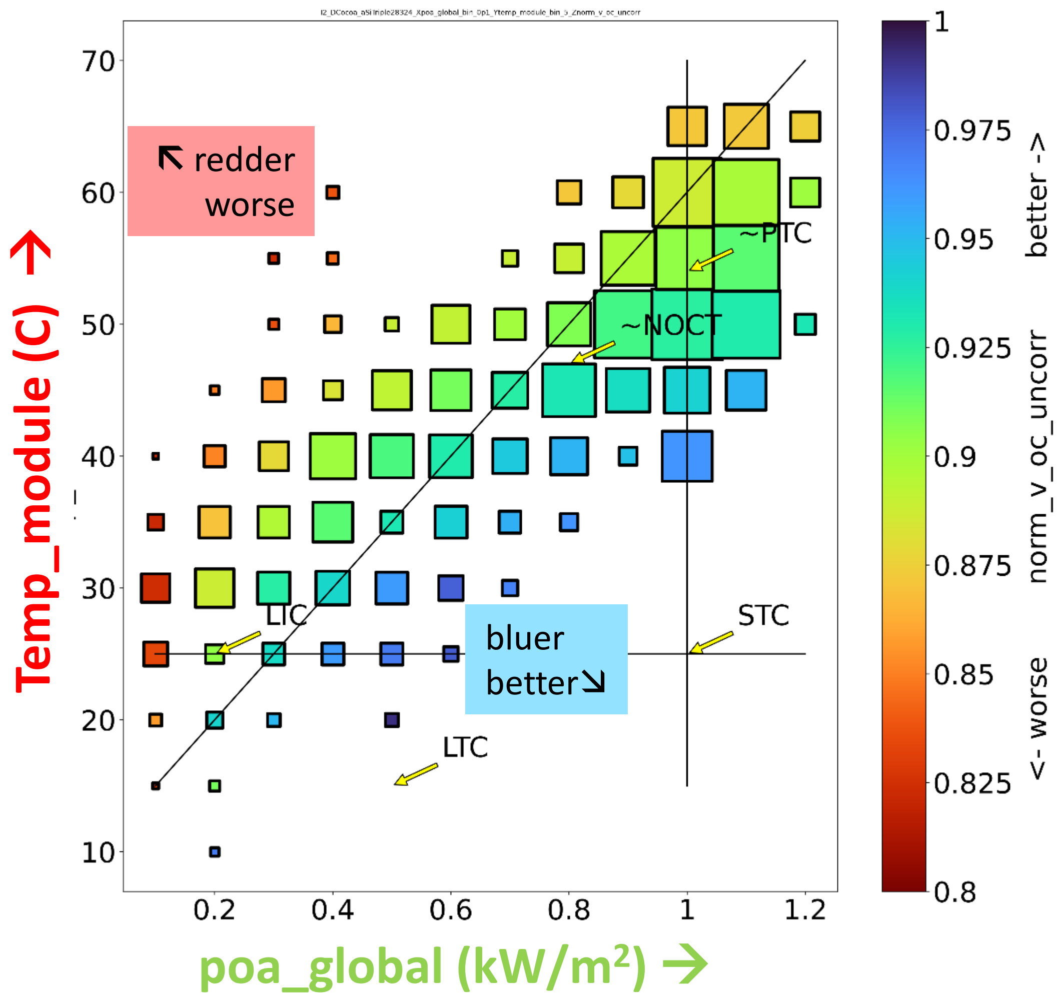
- Point distribution
- Non-unique best fits
- "imperfections" such as mismatch, rollover, variable cloud during scan



Fit to MLFM

- 6+1 normalised losses from IV shape
- Characterises loss parameters vs. G, T and time

Improved matrix performance plot (with four independent parameters)



colour = chosen parameter

blue=best performance

green = middle

red=worst performance

Area of squares :

α insolation H (kWh/m²/y)

- Some standard conditions are marked e.g. STC, NOCT
- Area shows most important (large) vs. insignificant (very small) which may be outliers

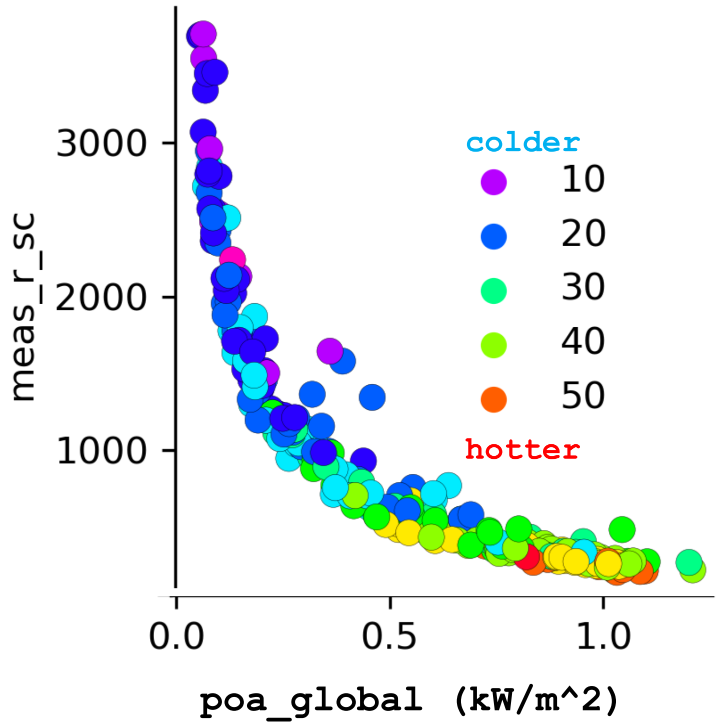
- **Many existing studies only model p_mp or pr_dc**

- **A few study i_sc, v_oc or ff**

- **But very few look at r_sc (~r_shunt) and r_oc(~r_series) which are important for energy yield and degradation**

Analysing r_sc [~ r_shunt]

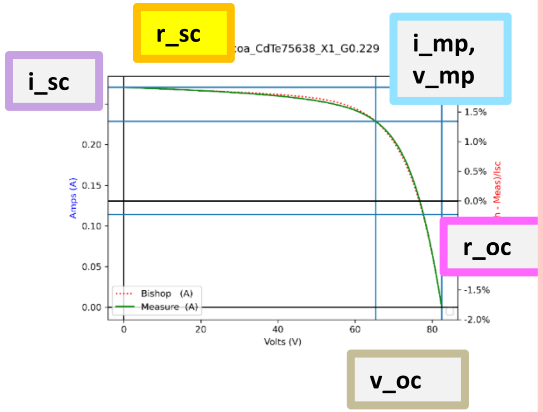
meas_r_sc(G, T) Ω scatter



“r_sc is curved with a small -ve T sensitivity”

Most models assume :
r_sc=constant or ~1/G

PVSYST has exponential fit

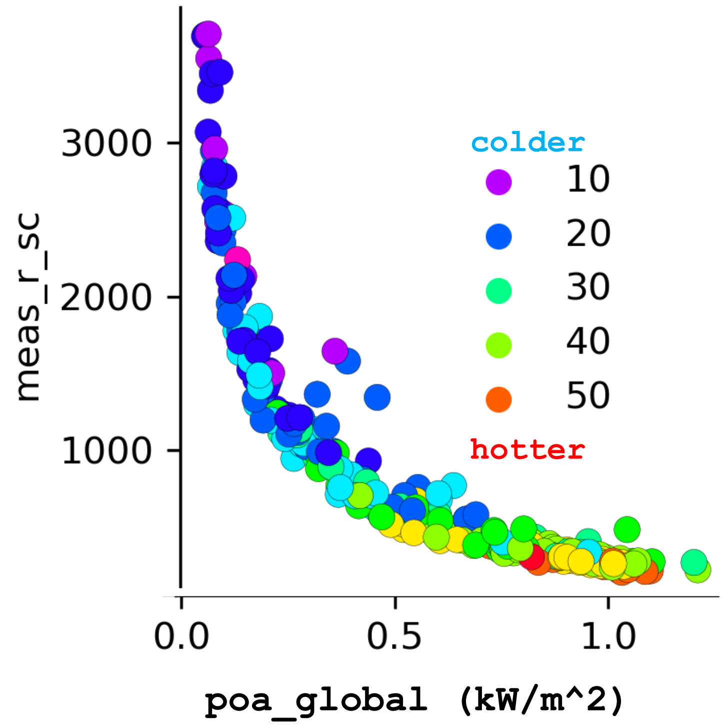


$$r\_sc = -1/\left(\frac{dI}{dV_{@V=0}}\right) \sim r\_shunt$$

Analysing r_sc [~ r_shunt]

Square area proportional to Insolation (kWh/m²/yr)

meas_r_sc(G, T) Ω scatter



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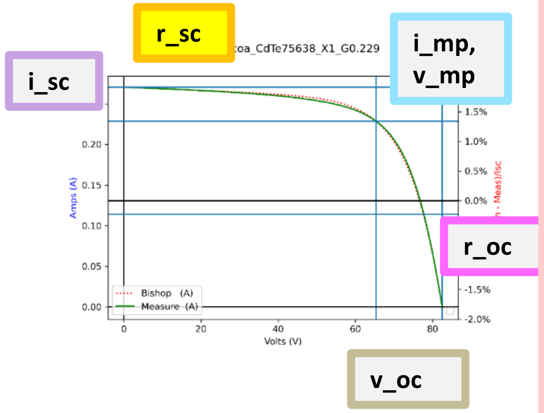
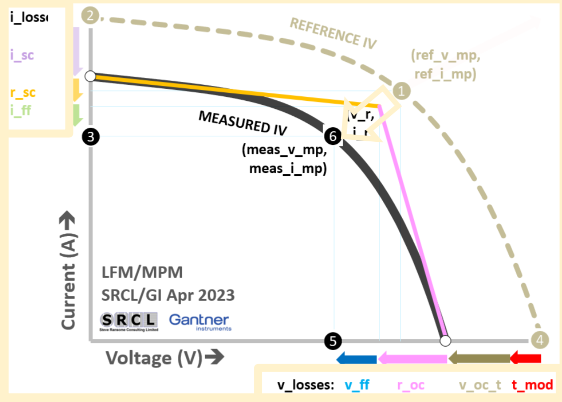
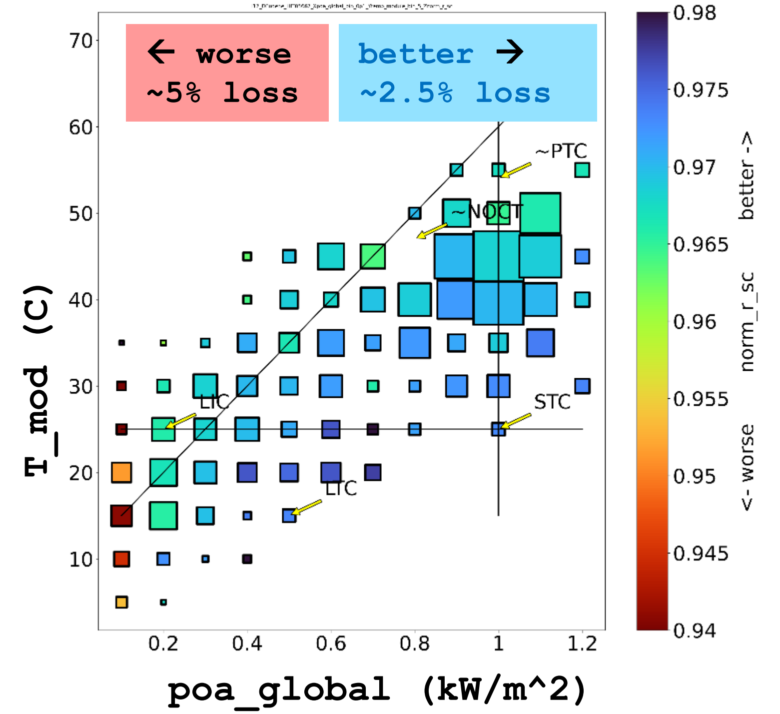


$$\text{r\_sc} = -1/\left(\frac{dI}{dV_{@V=0}}\right) \sim \text{r\_shunt}$$

r_sc



norm r_sc(G, T) % matrix



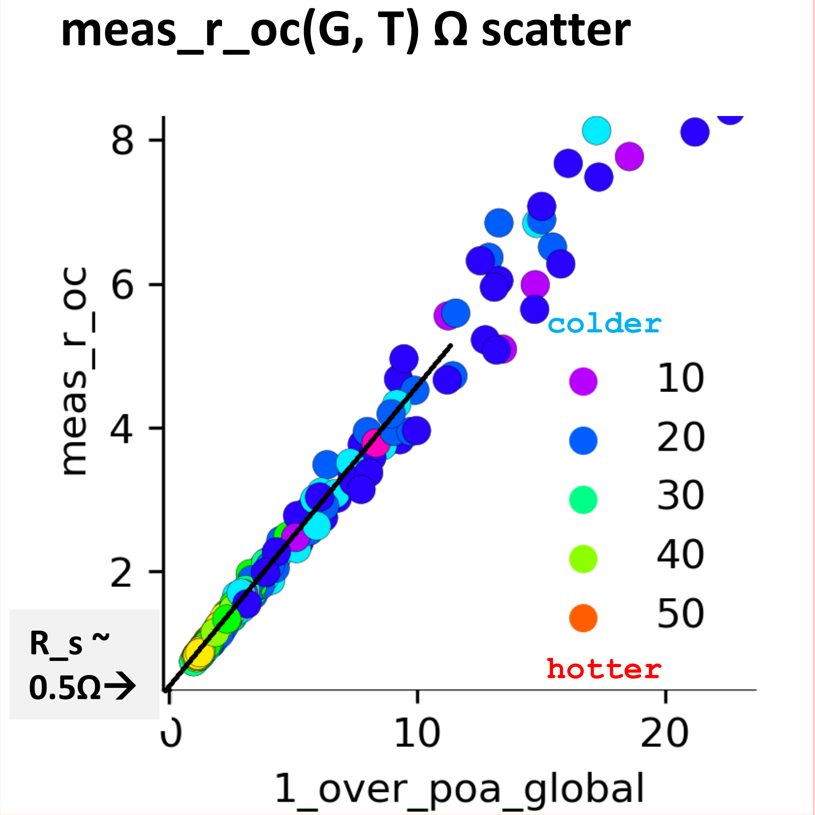
MLFM fit parameters

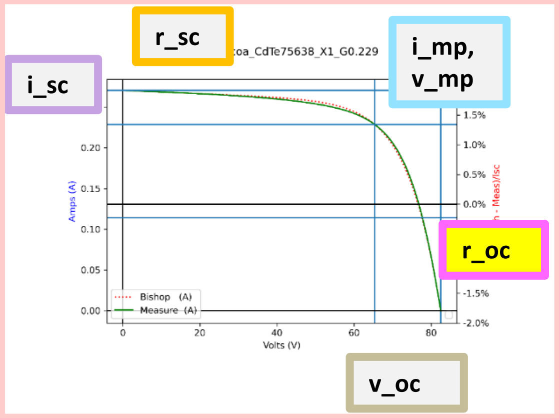
= c_1c +c_2t*(T-25)+c_3lg*LOG_{10}(G) +c_4g*G

Temp coeff Good fit

mlfm	c_1c	c_2t	c_3lg	c_4g	rmse
norm_r_sc	98.3%	-0.07%	3.0%	-0.3%	1.1%

Analysing r_oc [~ r_series]





$$\text{r\_oc} = -1/\left(\frac{dI}{dV_{@I=0}}\right)$$
$$= \text{r\_series} + \text{fn}(1/G)$$

"r_oc~linear v.s 1/G, = r_s @ 1/G→0"

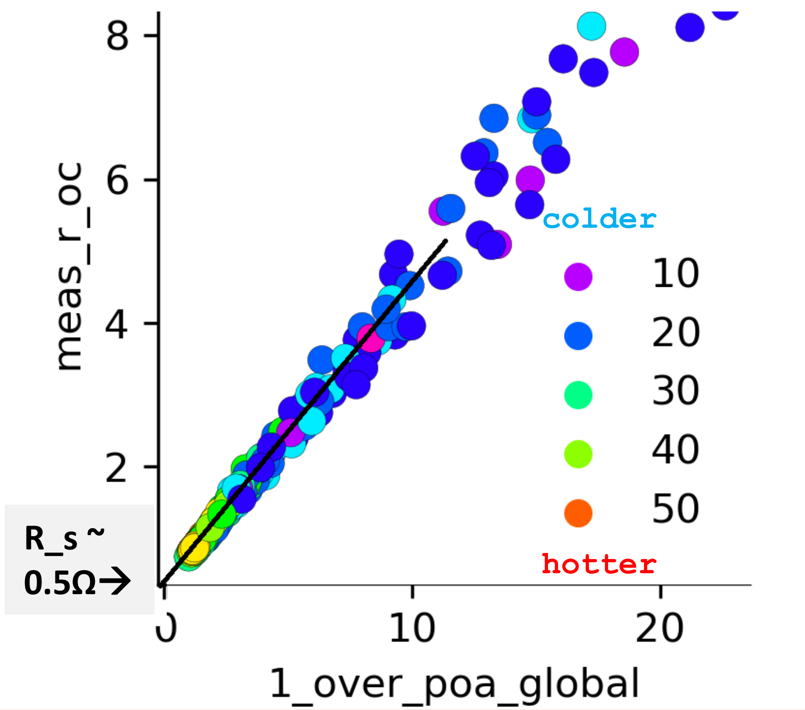
Small Temp. coeff. dependent on Technology

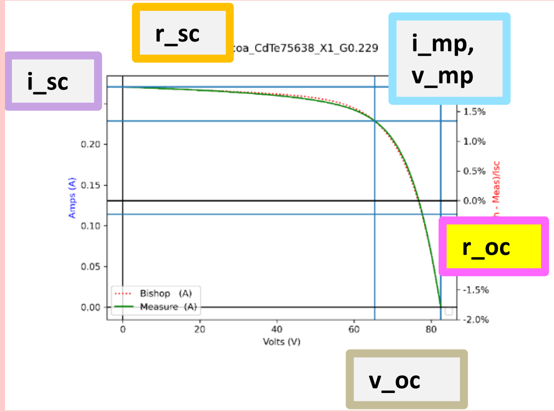
d/dT <0 for cSi (metal), >0 for Thin films (TCO)

Most models: r_s(G, T) = constant

Analysing r_oc [~ r_series]

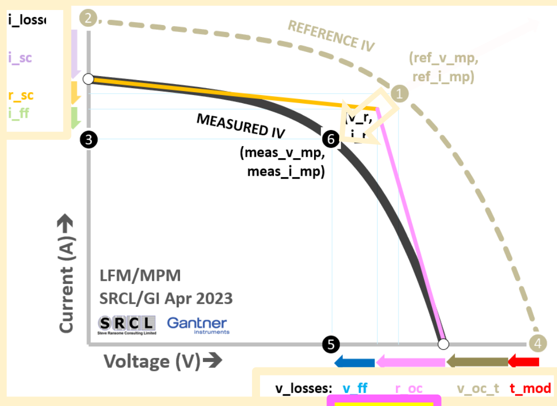
meas_r_oc(G, T) Ω scatter





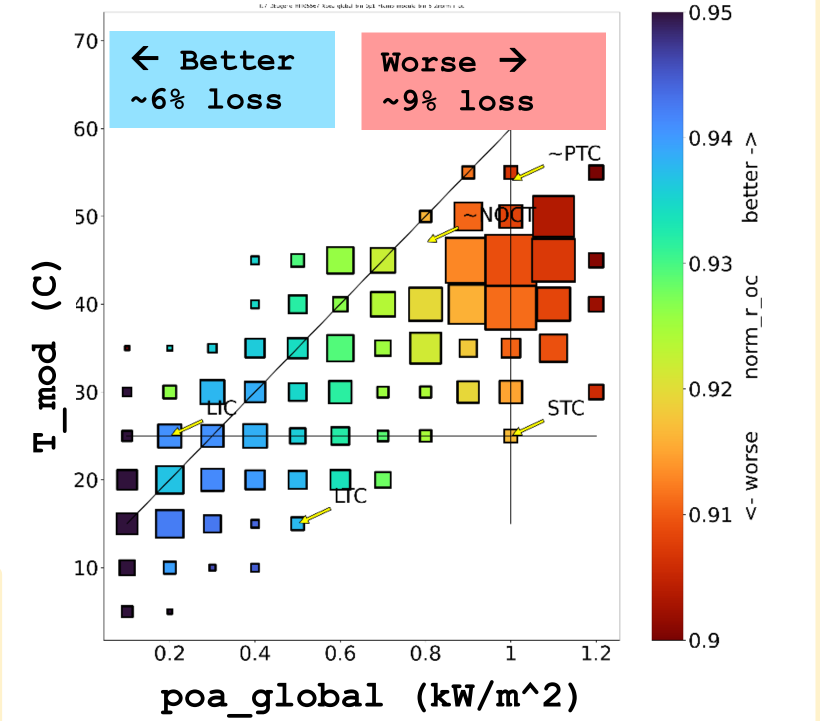
r_oc $= -1/\left(\frac{dI}{dV_{@I=0}}\right)$

= r_series + fn(1/G)



Square area proportional to Insolation (kWh/m²/yr)

norm r_oc(G, T) % matrix



"r_oc~linear v.s 1/G, = r_s @ 1/G→0"

Small Temp. coeff. dependent on Technology

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Most models: r_s(G, T) = constant

MLFM fit parameters

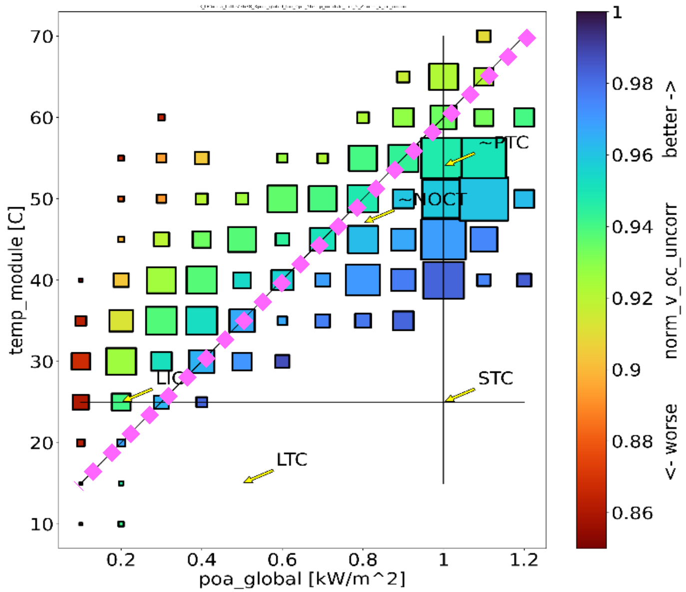
= c_1c +c_2t*(T-25)+c_3lg*LOG$_{10}$(G) +c_4g*G

		Temp coeff			Good fit
mlfm	c_1c	c_2t	c_3lg	c_4g	rmse
norm_r_oc	97.7%	-0.04%	3.8%	-6.3%	1.5%

Checking performance at different sites or times (degradation etc.)

(CdTe, norm_v_oc = colour, irradiance➔ module temperature🡅)

Site A) Florida (Mod #1)



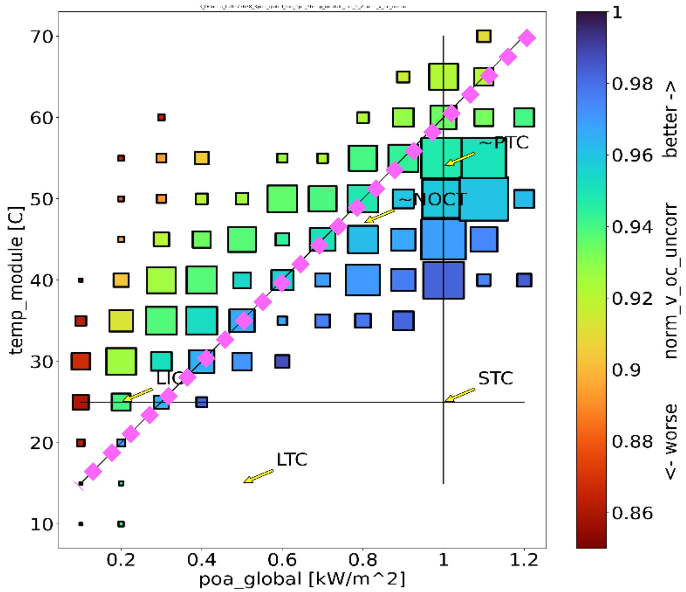
Square area proportional to Insolation ($kWh/m^2/yr$)

$= c\_1c + c\_2t*(T-25) + c\_3lg*LOG_{10}(G) + c\_4g*G$

Checking performance at different sites or times (degradation etc.)

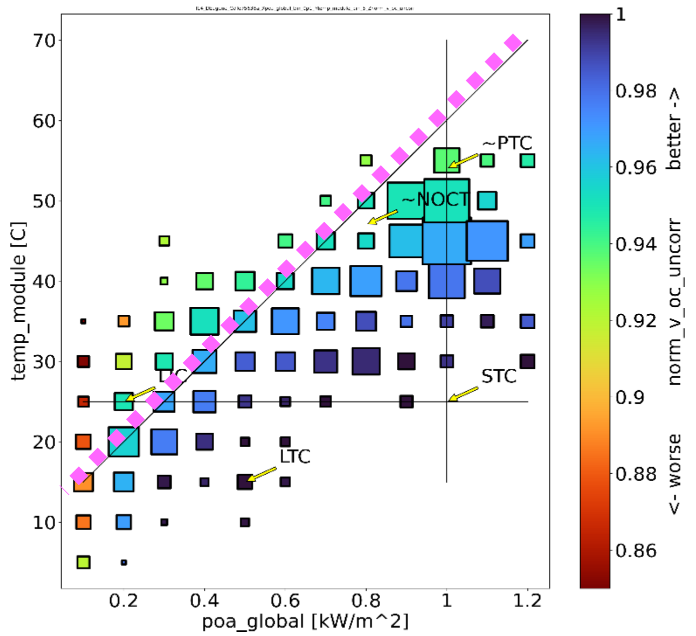
(CdTe, norm_v_oc = colour, irradiance→ module temperature↑)

Site A) Florida (Mod #1)

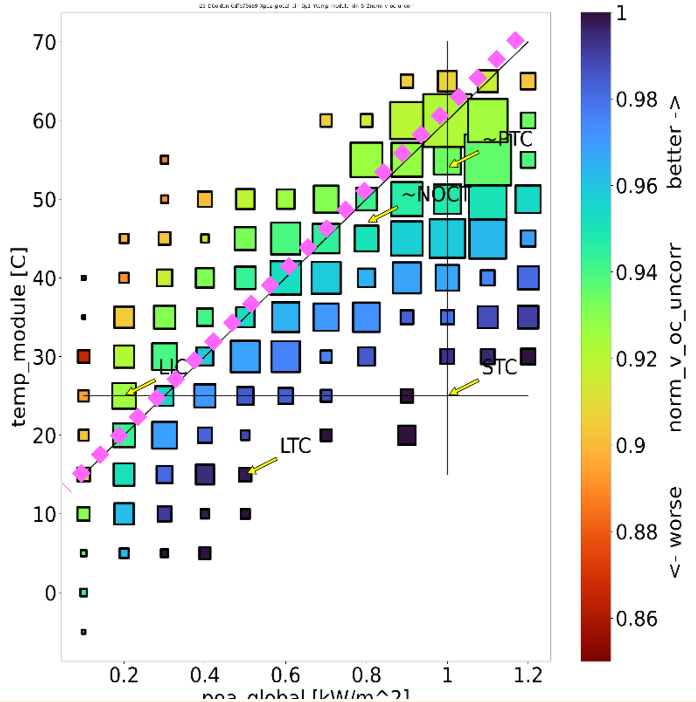


= c_1c +c_2t*(T-25)+c_3lg*LOG_{10}(G) +c_4g*G

Site B) Oregon (Mod #1)



Site C) Colorado (Mod #2)



Any performance changes would show up in MLFM fit coefficients and colours at given conditions e.g. STC

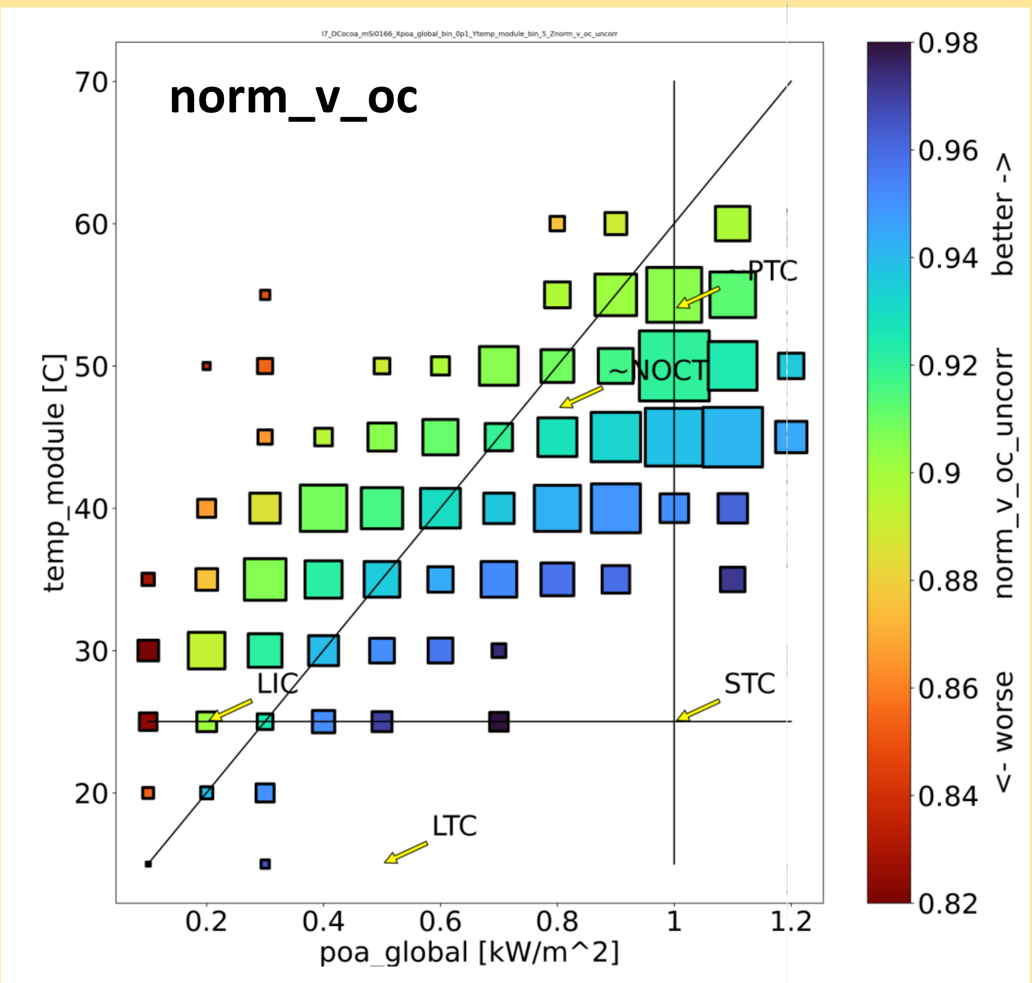
State	Mod	param	c_1c	c_2t	c_3lg	c_4g	rmse	STC	LIC	NOCT	HTC
FL	CdTe	norm_v_oc	104.9%	-0.27%	14.0%	-3.0%	0.40%	101.9%	94.5%	95.8%	88.6%
CO	CdTe	norm_v_oc	102.3%	-0.25%	11.6%	-1.9%	0.39%	100.4%	93.8%	94.6%	87.9%
OR	CdTe	norm_v_oc	105.1%	-0.28%	13.9%	-3.6%	0.83%	101.5%	94.7%	95.2%	87.4%

Square areas proportional to Insolation (kWh/m²/yr) differ due to climates

Characterising temperature coefficients (e.g. α_isc, β_voc, γ_pmp)
Do they vary with (G, T) or are they constant ?

Most models assume Temperature Coefficients temp_coeff(G, T) = constant

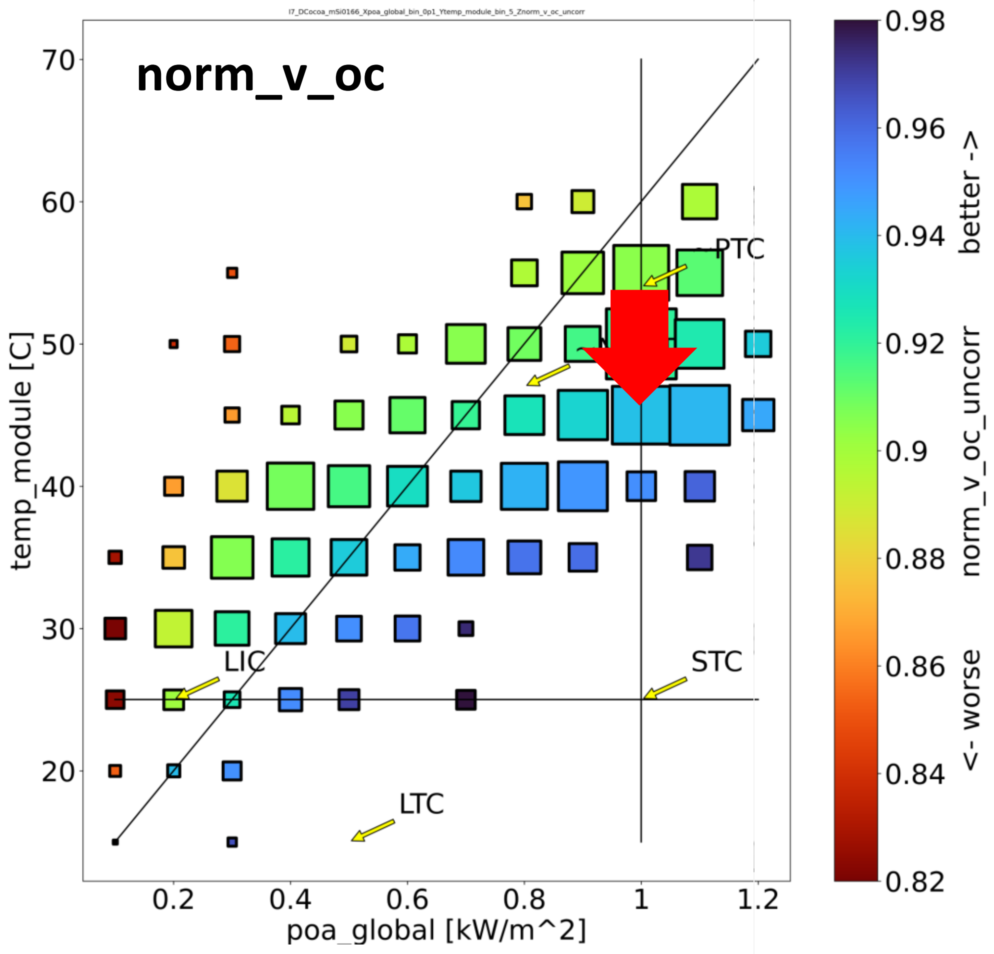
Some manufacturers may provide valid ranges if they vary e.g. “>25C”



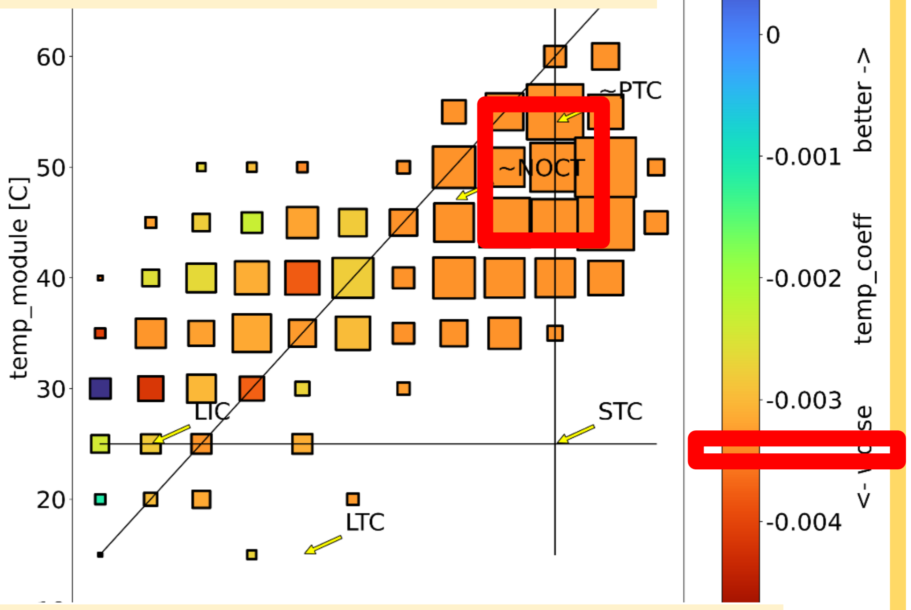
Characterising temperature coefficients (e.g. α_isc, β_voc, γ_pmp)
Do they vary with (G, T) or are they constant ?

temp_coeff(G,T) =
difference between adjacent points
Usually measured just at STC

This method with 50-100 points allows us to easily map a temp_coeff(G,T) from a normalised loss matrix



beta_voc =Δ(norm_v_oc) / ΔT



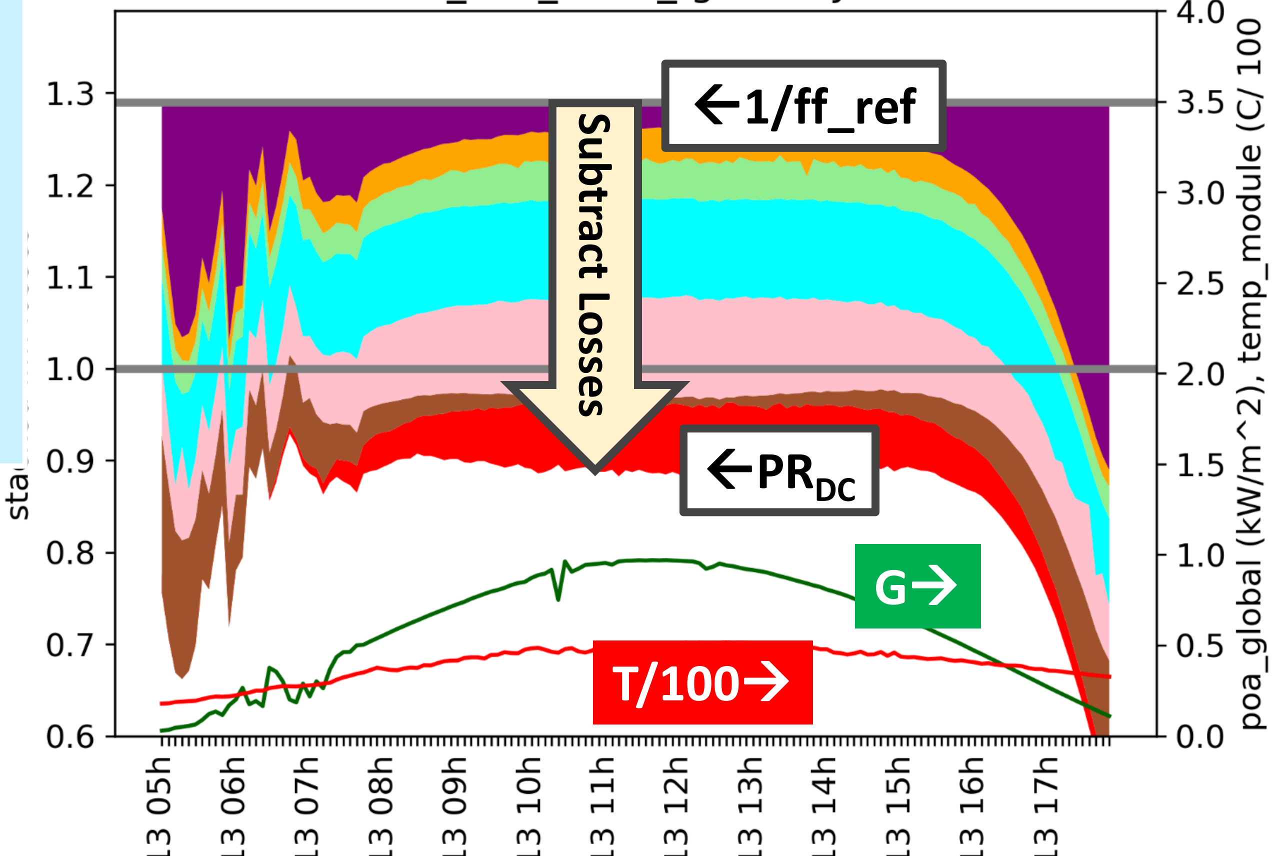
Note :
Not yet tested on OPV, perovskite, dye or novel tandem

This example :
Some scatter but ~uniform -0.35%/K

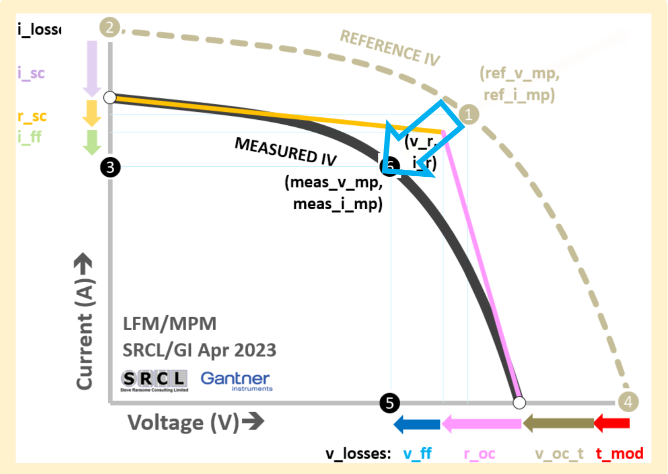
How do the different performance losses vary with G and T?

Subtract all 7 losses in turn from

1/ff_ref
🡻
PRdc



1 clear day



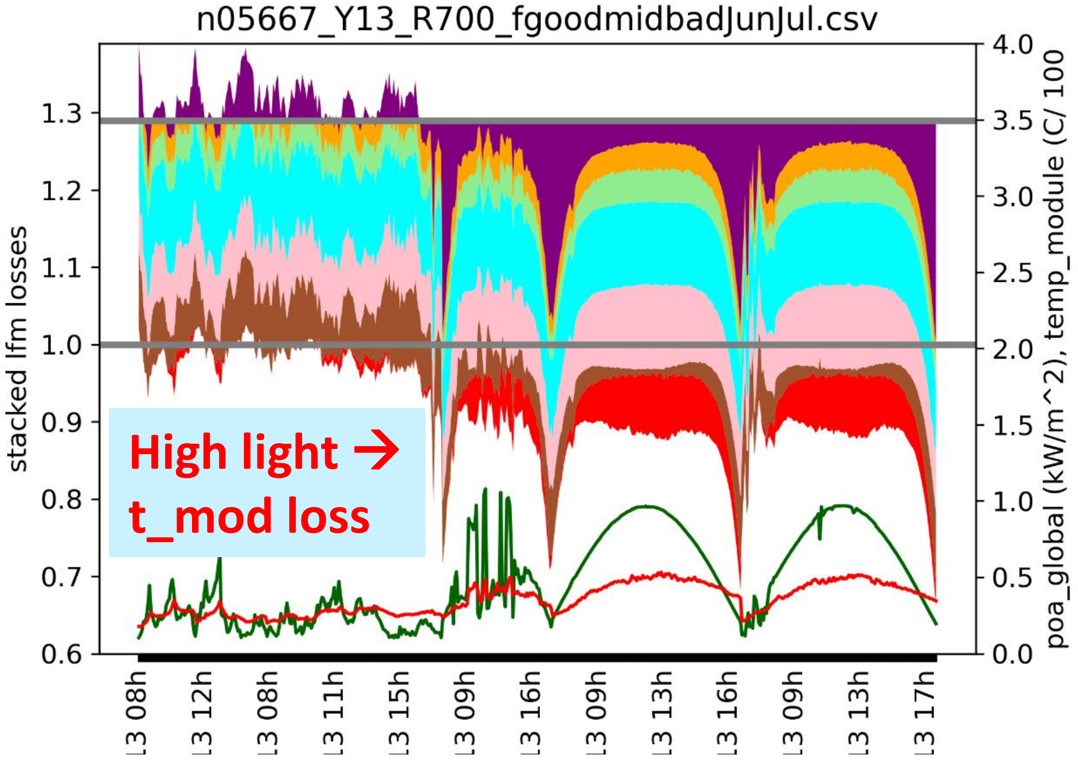
Loss KEY :

i_sc	(AOI, spectra, soil)
r_sc	(~Rshunt)
i_ff	(fill factor I drop)
v_ff	(fill factor V drop)
r_oc	(~Rseries)
v_oc-T	(Voc temp corrected)
t_corr	(temp correct)

Stacked losses under different weather conditions (cloudy then bright days)

(no correction for reflectivity or spectral response from pyranometer)

HIT 2010



3Cloudy 1Variable 2Sunny

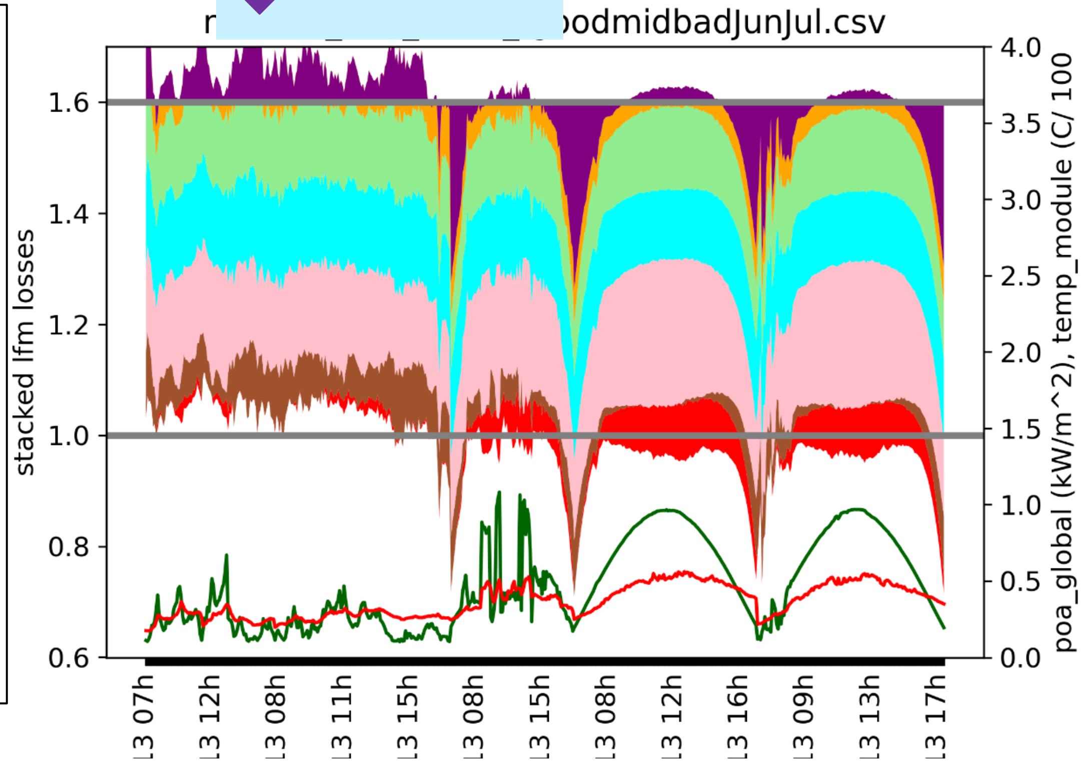
Loss KEY :

- i_sc
- r_sc
- i_ff
- v_ff
- r_oc
- v_oc-T
- t_corr

Irrad kW/m² →
Tmod C/100 →

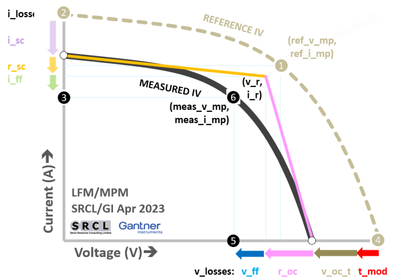
CdTe 2010

Low light
Spectral gains
↓

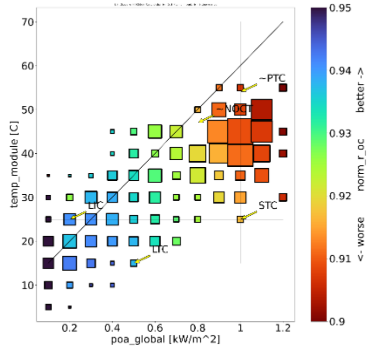


3Cloudy 1Variable 2Sunny

Conclusions



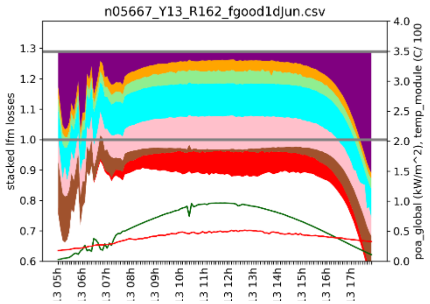
New methods have been shown using normalised loss factors to improve IV curve and matrix fits finding temperature and performance coefficients



Matrix plots (with areas ~ Insolation) are easiest to visualize and fit

Losses and causes help understand the behaviour vs. G,T and time

Please contact me for more information steve@steveransome.com



Thank you for your attention!

DATA : **https://www.nrel.gov/docs/fy14osti/61610.pdf**