Getting more useful information from modelling of iv curves and matrix measurements

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Existing modelling methods give reasonable energy yield estimates, but there are simple analysis methods that can be done to

- **differentiate PV technologies** — (from r_series, r_shunt etc.)
- **partition PR losses into separate causes** — (e.g. v_oc, r_sc)
- **find what may be limiting performance** — (e.g. r_oc is high)
- **calculate degradation rates for each loss factor under different weather conditions** — (e.g. r_sc fall causes higher degradation at low G)
- **be able to suggest optimization targets** — (e.g. reduce r_series)

This talk suggests some improvements to modelling methods, normalizing of measurements, loss and graphical analysis

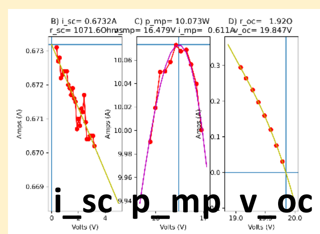
Outdoor data used for this study

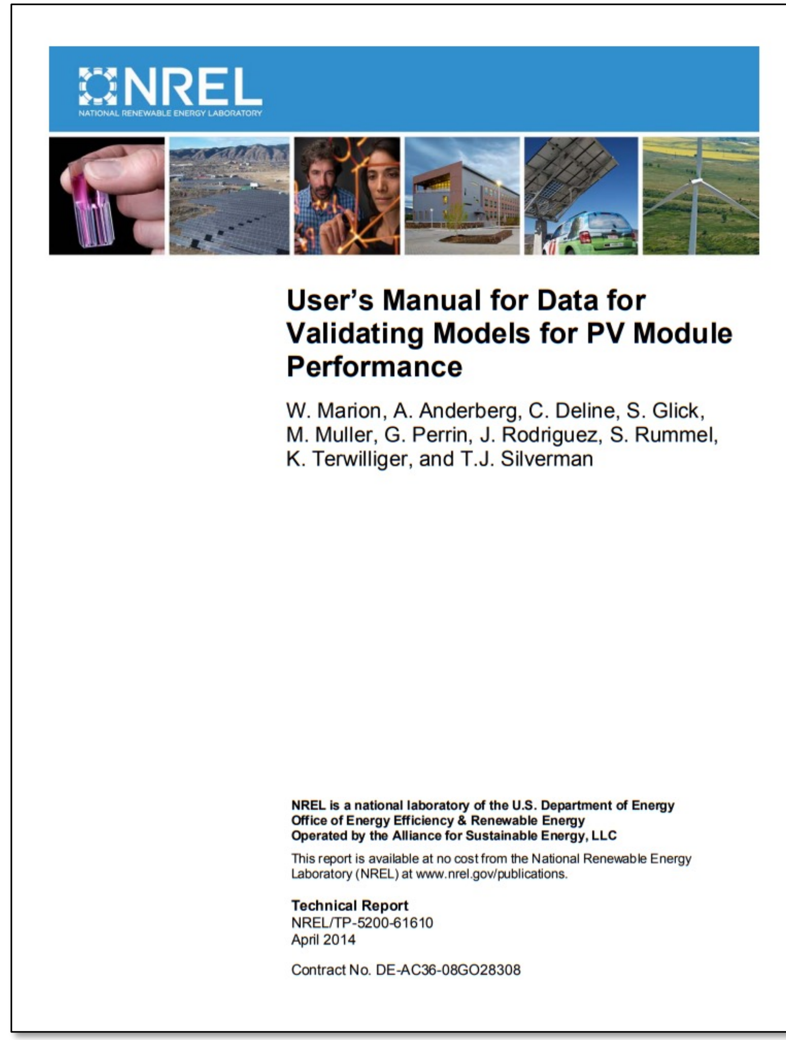
https://www.nrel.gov/docs/fy14osti/61610.pdf

- ☑ 11 modules of different technologies (CdTe, CIGS, aSi, 3JaSi, mcSi, scSi, HIT …)
- ☑ Measured 3 sites FL, CO, OR for >1year
- ☑ ~180 IV points for curves each 5-15 mins
- ☑ Pyranometers for G_POA, DHI, GHI, BNI
- ☑ Soiling, precipitation, RH (ignored here)
- ☑ Fits to i_sc, i_mp, v_mp, v_oc were given

However

- ☒ No windspeed
- ☒ No spectrum
- ☒ No r_sc or r_oc fits but calculated here →




NREL
NATIONAL RENEWABLE ENERGY LABORATORY

User's Manual for Data for Validating Models for PV Module Performance

W. Marion, A. Anderberg, C. Deline, S. Glick, M. Muller, G. Perrin, J. Rodriguez, S. Rummel, K. Terwilliger, and T.J. Silverman

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

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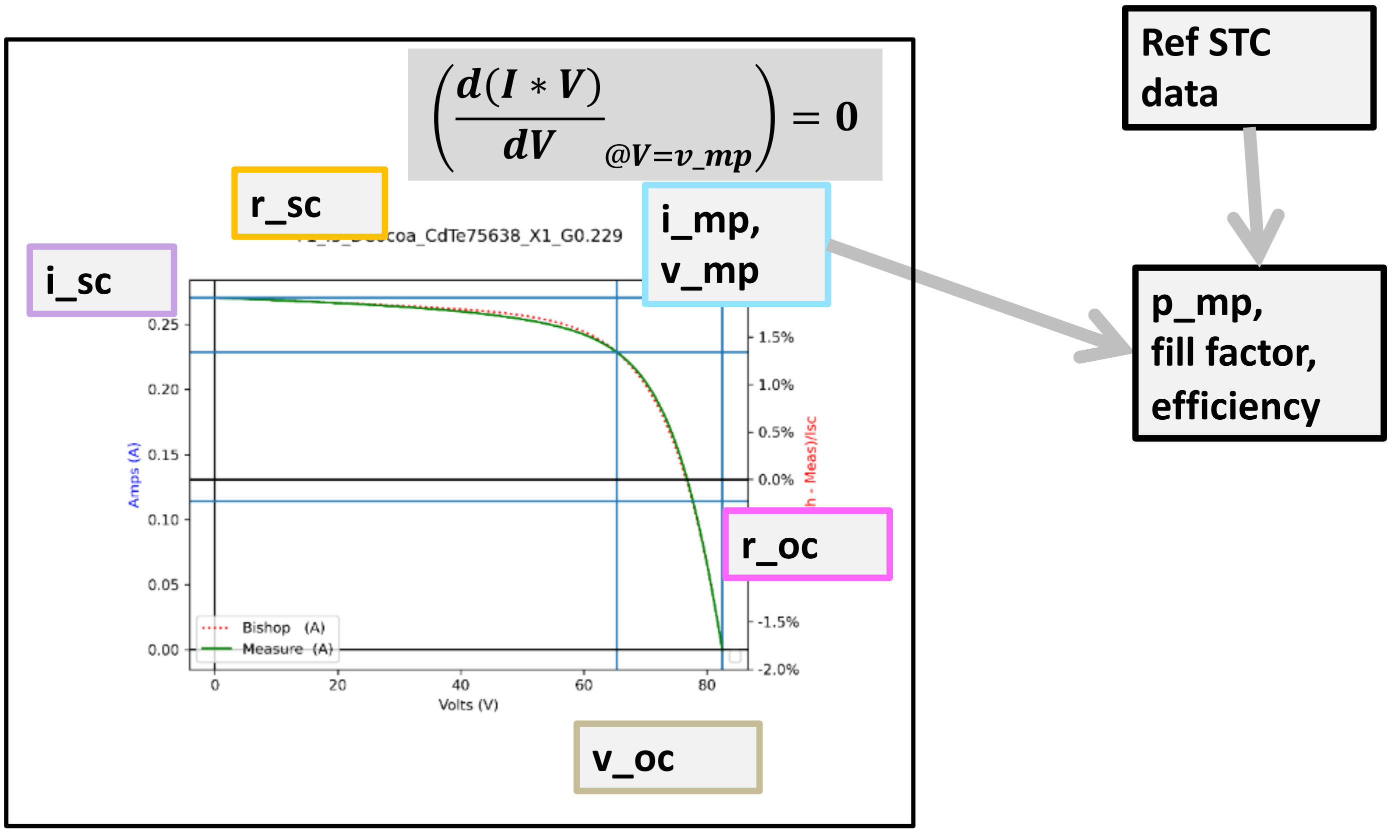
Technical Report
NREL/TP-5200-61610
April 2014

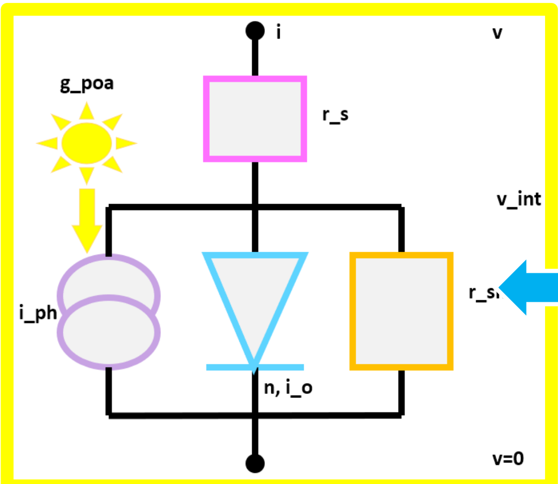
Contract No. DE-AC36-08GO28308

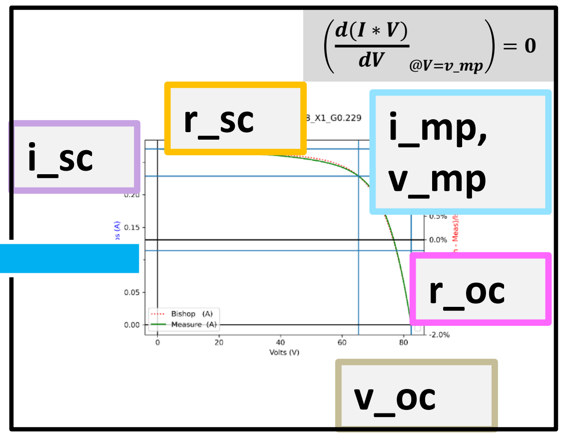
Typical measured NREL IV curve with some fitted parameters (A, V, Ω, W)



IV curve → 1-diode model fit with 5 components

color shows which component ‘dominates’ each fit parameter

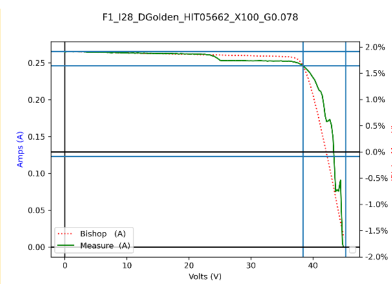




1-diode best fits to IV curves are limited by

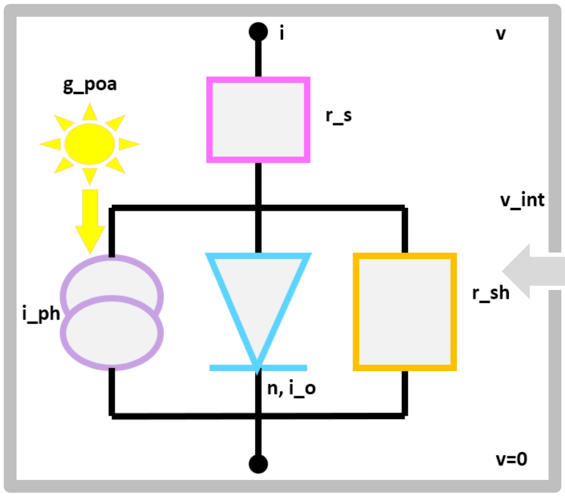
- **Point distribution : e.g. “poor r_shunt fit if few near i_sc”**
- **Differing fit algorithms, non-unique best fits**
- **“imperfections” mismatch, rollover, variable cloud during scan**
- **Note : 5 variables are insufficient to fit all IV curves perfectly**

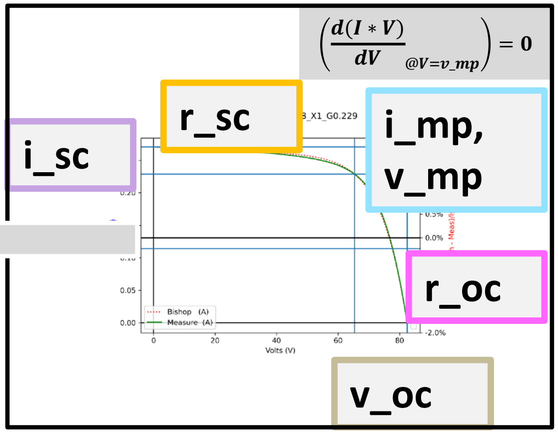
→

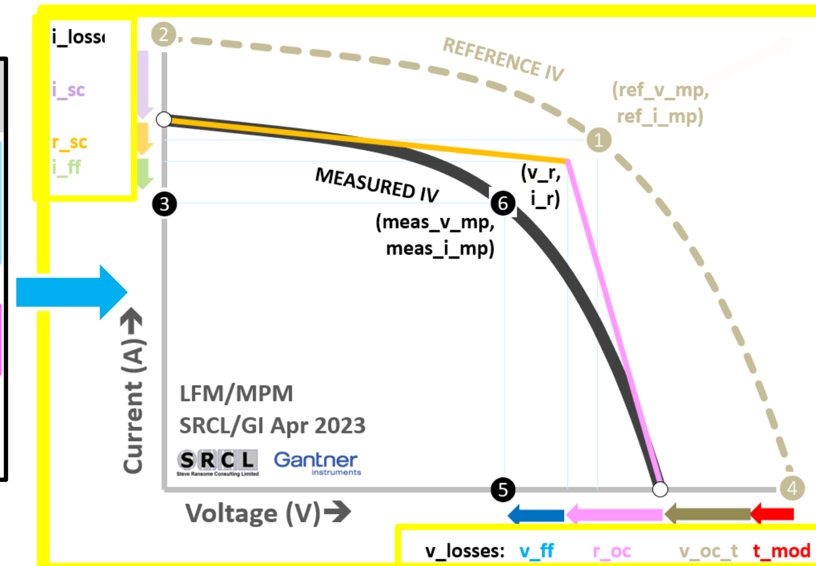


IV Curve → MLFM* fit with 6 normalised electrical and 1 temperature correction

*** mechanistic loss factors model**

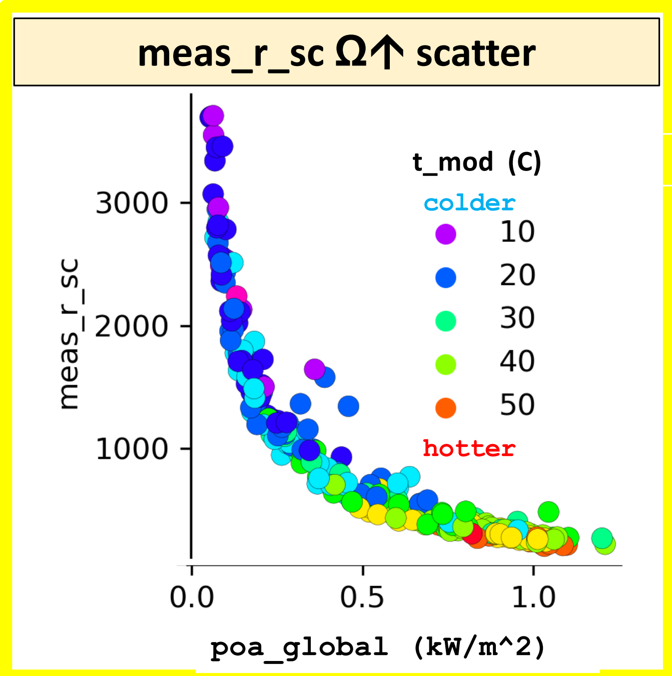




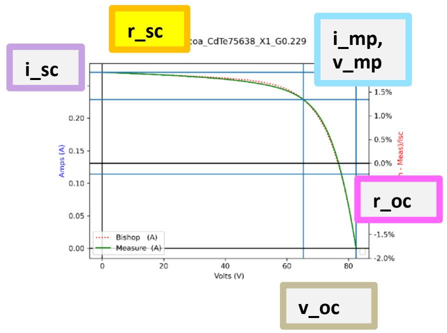


- **6+1 normalised losses from IV curve shape**
- **Characterise loss parameters vs. G, T and time**

Analysis of r_sc(G, T)



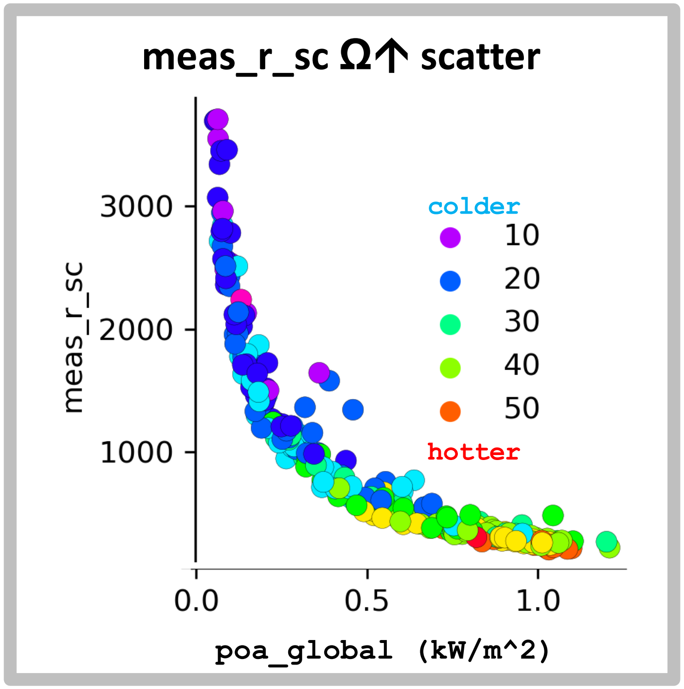
$$\text{r\_sc} = -1/\left(\frac{dI}{dV_{@V=0}}\right) \sim \text{r\_shunt}$$



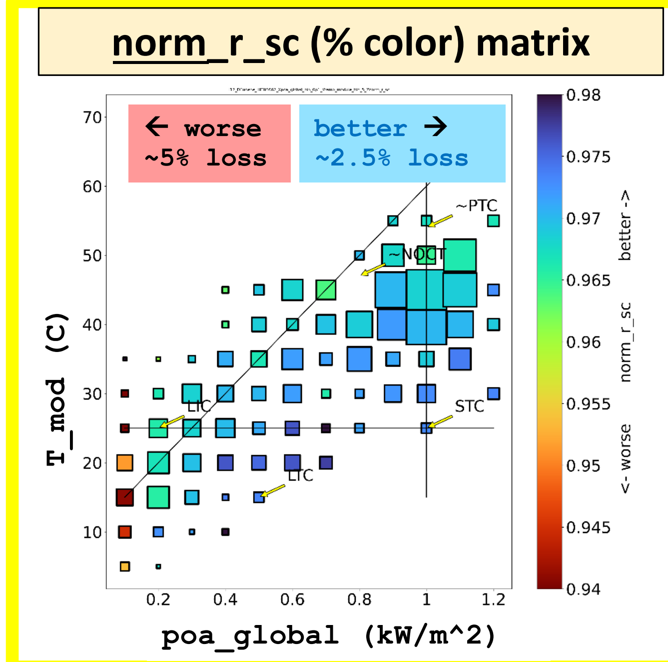
r_sc vs. G is curved with a small -ve T sensitivity.
Most models assume r_sc=constant or r_sc~1/G
PVSYST has exponential fit

HIT module shown –
c-Si and thin films all have similar shapes
(but differing values)

Analysis of r_sc(G, T)



Improved analysis of r_sc(G, T)



SImilar fits can be done for any normalised parameters

Outdoor Matrix : has 50-100 useful G,T points

IEC 61853 (indoor) has ~28 (trying to reduce to ~6 for cost savings)

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

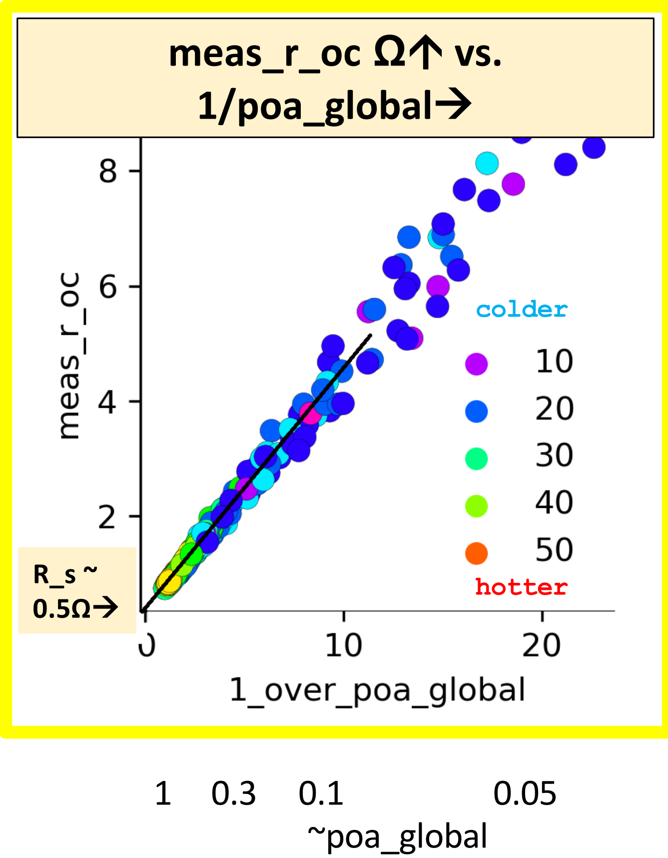
MLFM Good fit to norm_r_sc(G,T)
Temperature coefficient from fit as c_2t →

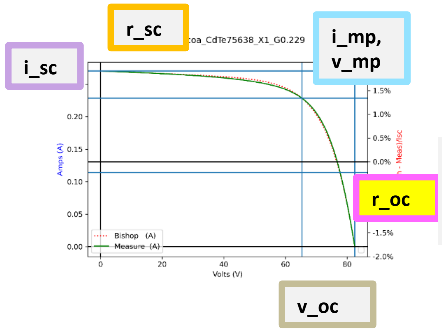
mlfm	c_1c	c_2t	c_3lg	c_4g	rmse
norm_r_sc	98.3%	-0.07%	3.0%	-0.3%	1.1%

```
mlfm fit norm_r_sc =
=c_1c+c_2t*(T-25)+c_3lg*LOG10(G)+c_4g*G
```

Mlfm calcs	STC	LIC	NOCT	HTC
norm_r_sc	97.4%	95.6%	96.4%	95.4%

Analysis of r_oc(G, T)



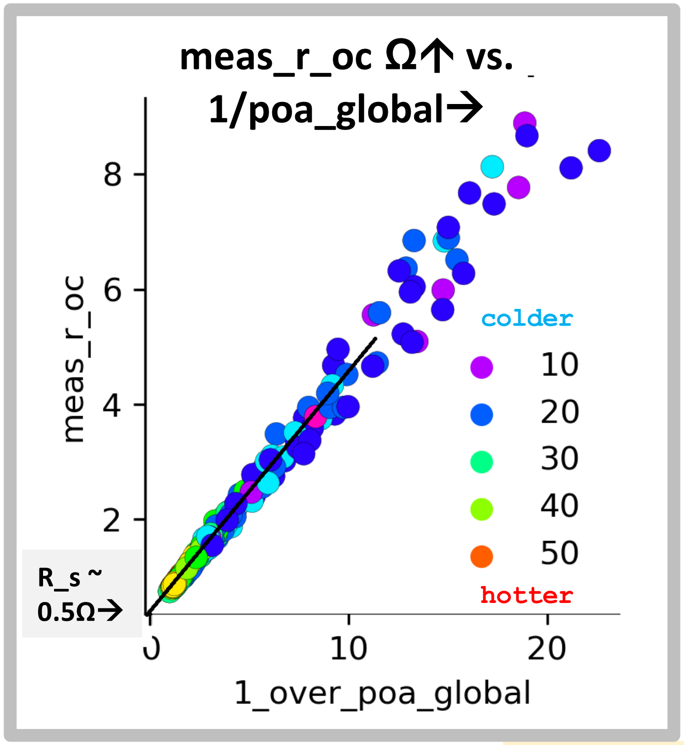


$$r\_oc = -1/\left(\frac{dI}{dV_{@I=0}}\right) = r\_s + fn(1/G)$$

- r_oc~linear v.s 1/G, extrapolates to r_s at 1/G→0
- Small Temp. coeff. depends on technology, usually
  - d/dT(norm_r_oc) <0 for cSi (metal)
  - d/dT(norm_r_oc) >0 for Thin films (TCO)
- <u>Most models assume r_s(G, T) = constant</u>

Analysis of r_oc(G, T)

Improved analysis of r_oc(G, T)



SImilar fits can be done for any normalised parameters

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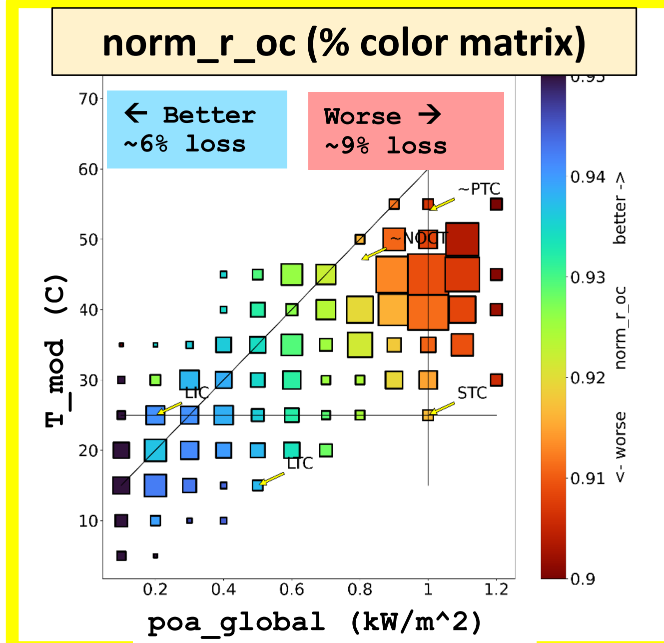


MLFM Good fit to norm_r_oc(G,T)

Temperature coefficient from fit as c_2t →

```
mlfm fit norm_r_oc =
=c_1c+c_2t*(T-25)+c_3lg*LOG10(G)+c_4g*G
```

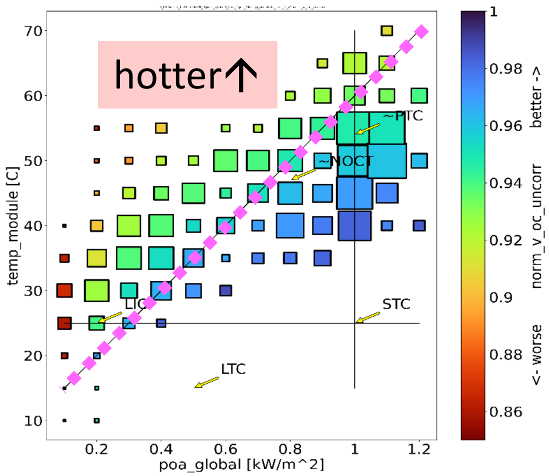
mlfm	c_1c	c_2t	c_3lg	c_4g	rmse
norm_r_oc	97.7%	-0.04%	3.8%	-6.3%	1.5%

Mlfm calcs	STC	LIC	NOCT	HTC
norm_r_oc	91.4%	93.8%	91.5%	89.4%

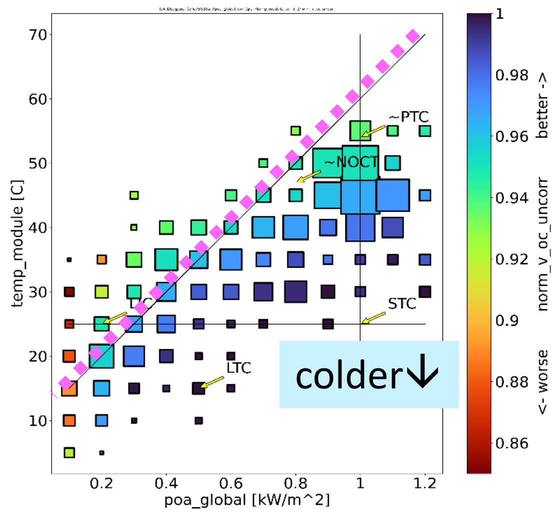
Performance at different sites or times

(CdTe, norm_v_oc = color)

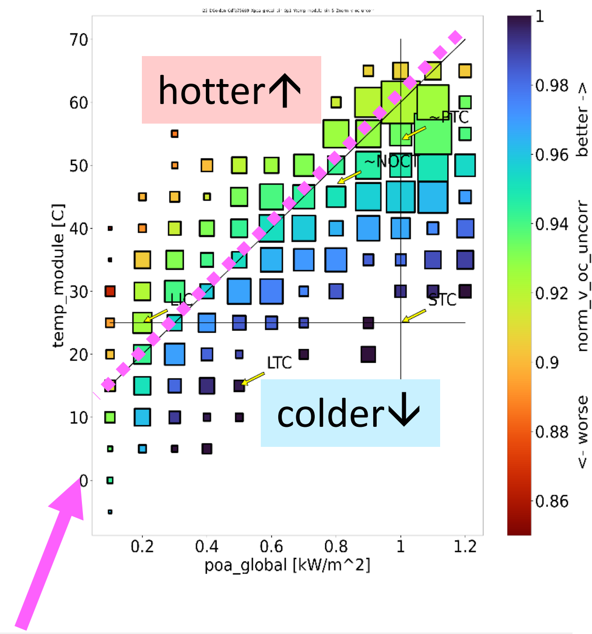
A) COCOA FLORIDA (#1)



B) EUGENE OREGON (#1)



C) GOLDEN COLORADO (#2)



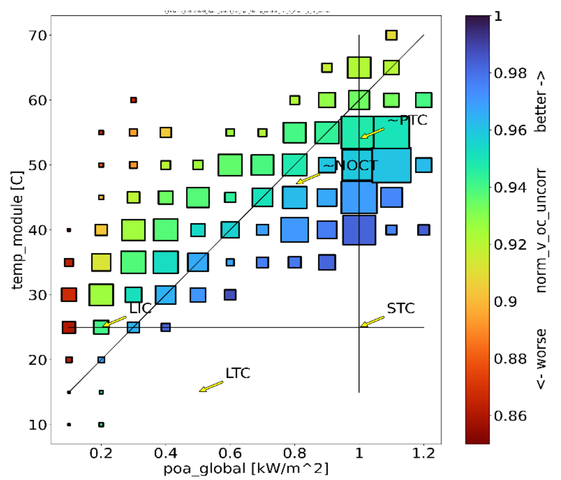
(Note: differing areas of squares from climates, distributions vs. temperature and irradiance)
There are reference lines at G=1, T=25 and a pink diagonal from (0.1,15) to (1.2,70)

Lower coldest temperature at Golden than others

Performance at different sites or times

(CdTe, norm_v_oc = color)

A) COCOA FLORIDA (#1)



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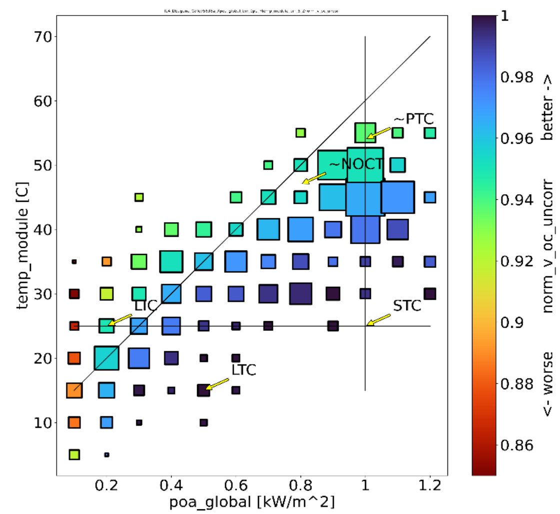
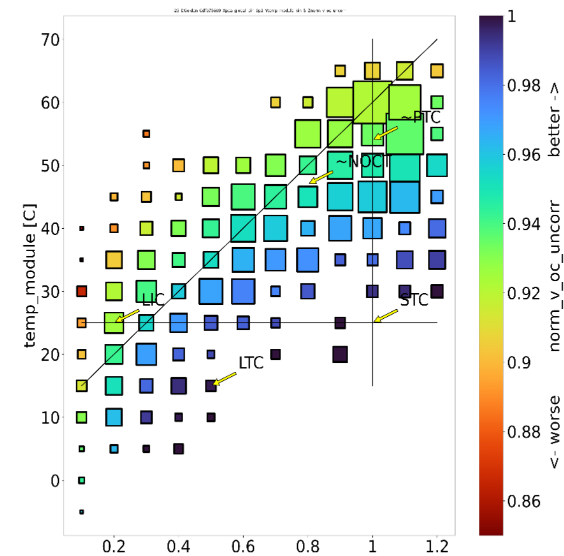


C) GOLDEN COLORADO (#2)



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

Any performance changes would show up in MLFM fit coefficients and values 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%

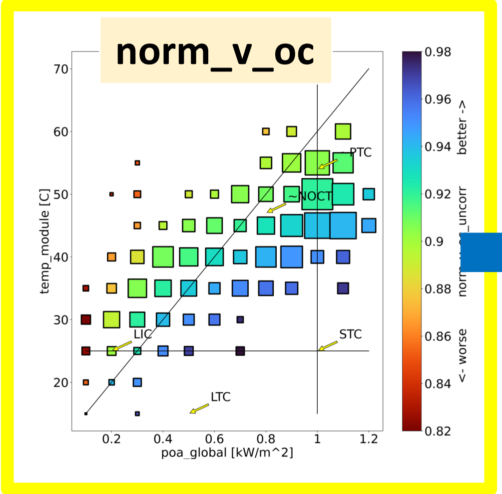
Does the temperature coefficient vary TC=fn(G, T) ?

`e.g. beta_v_oc(G, T) = 1/v_oc_STC * Δv_oc/ΔT`

- **Most models assume Temperature Coefficients TC(G, T) = constant**

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

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



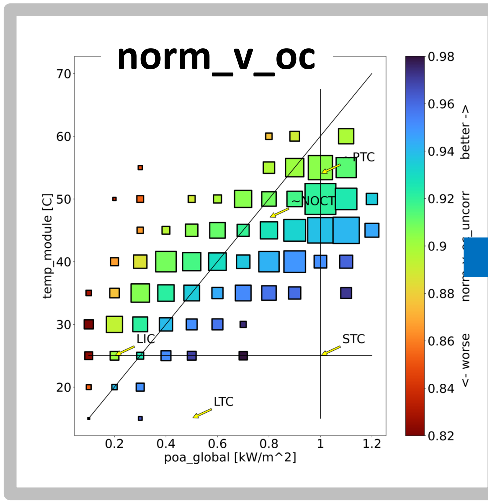
TC=fn(G, T) ?

Calculated Temperature coefficient TC=fn(G, T)

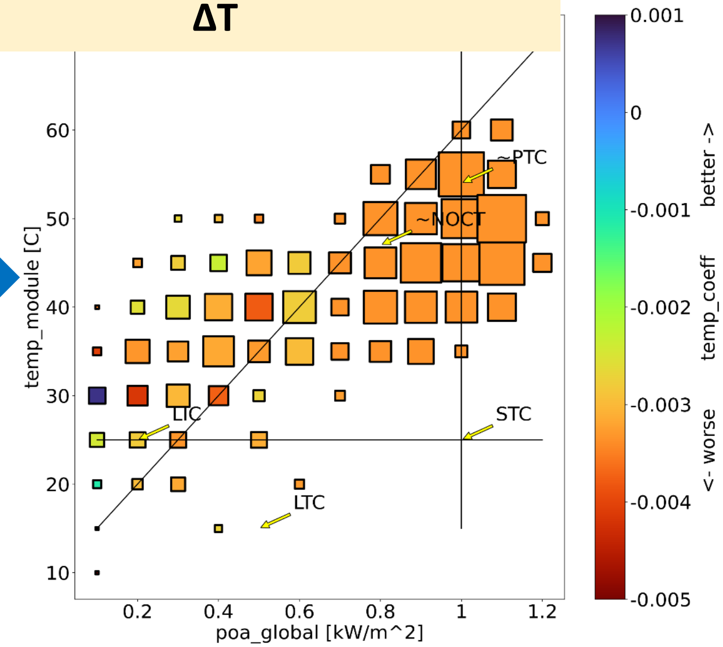
TC (G,T) = difference between adjacent temperature points⇳
mc-Si beta v_oc ~ -0.35%/K

Some astable thin films have “non-constant temp coeffs” where warm autumn performance
(after high temperatures) differs from cool spring (after cool weather)

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



beta_voc = $\frac{\Delta(\text{norm\_v\_oc})}{\Delta T}$



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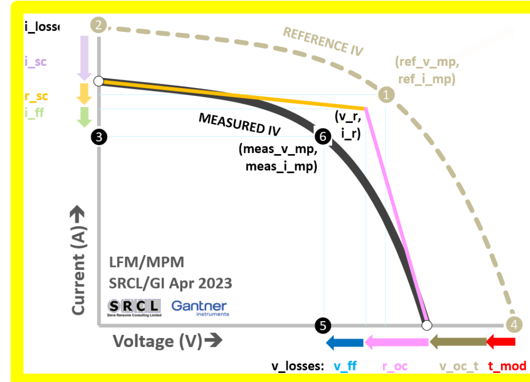
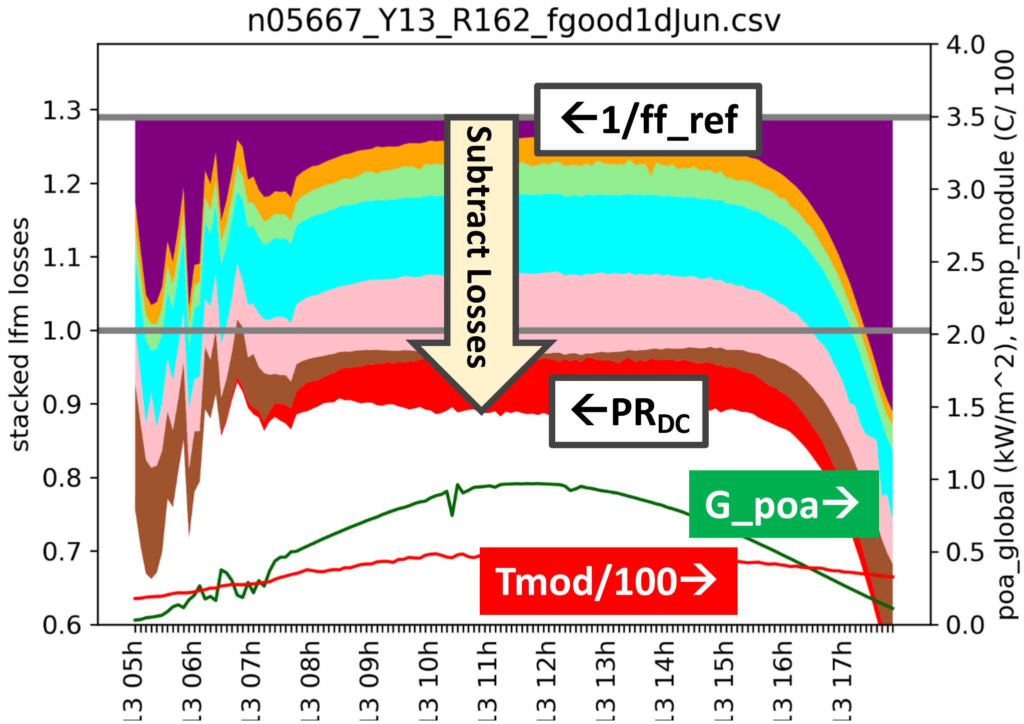
What are the performance losses by type vs. G and T?



Subtract all 7 losses in turn from

1/ff_ref
↓
PRdc



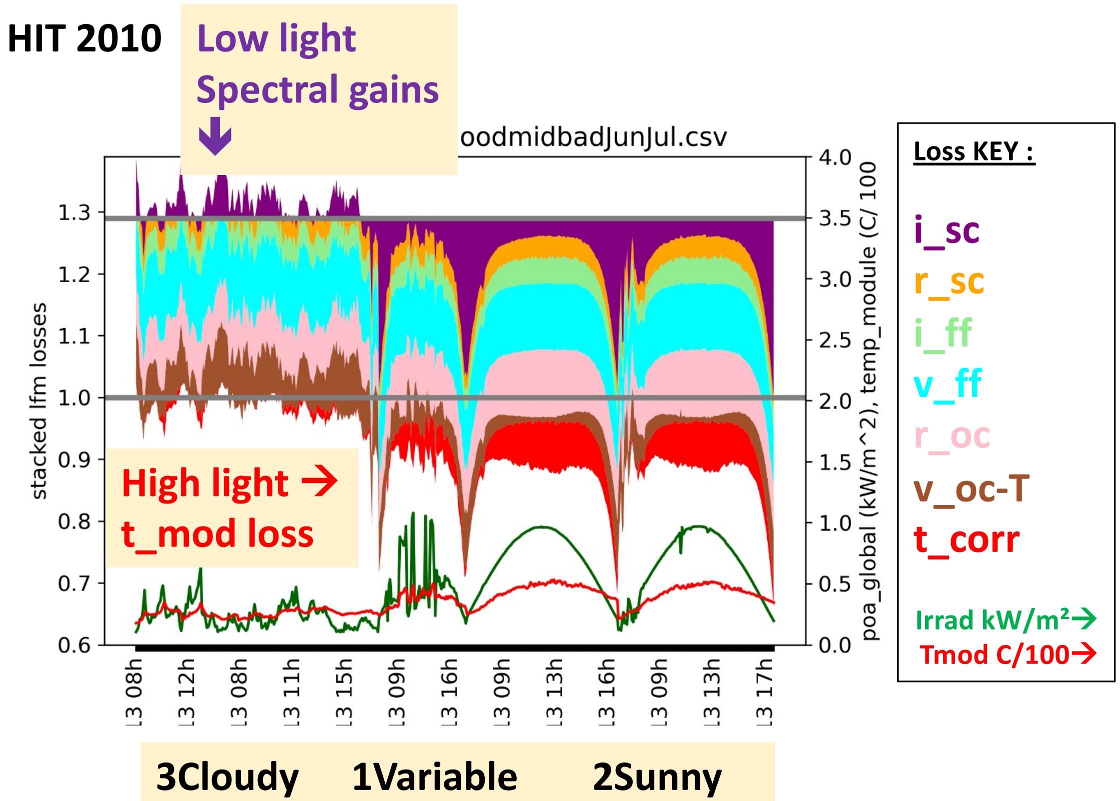
1 clear day

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)

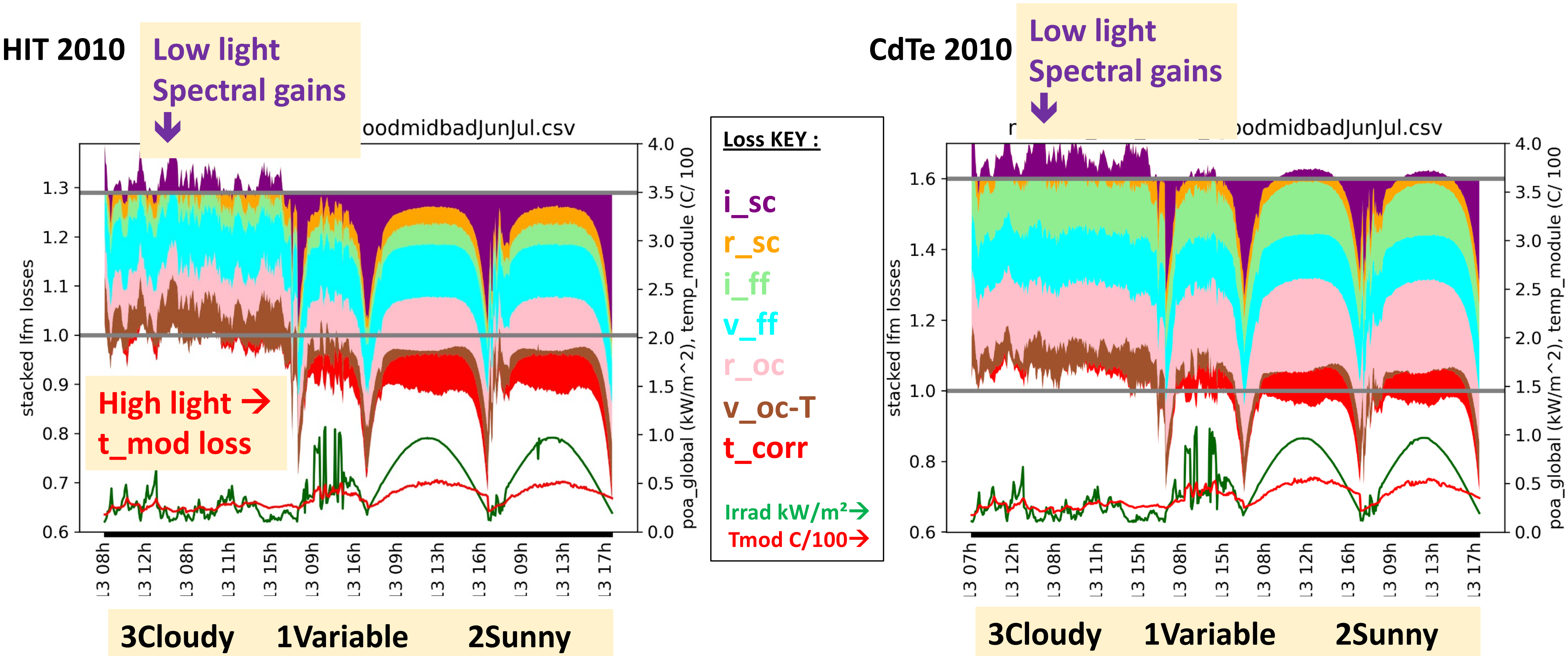
Stacked losses under different weather conditions

(no correction for reflectivity or spectral response from pyranometer)



Stacked losses under different weather conditions

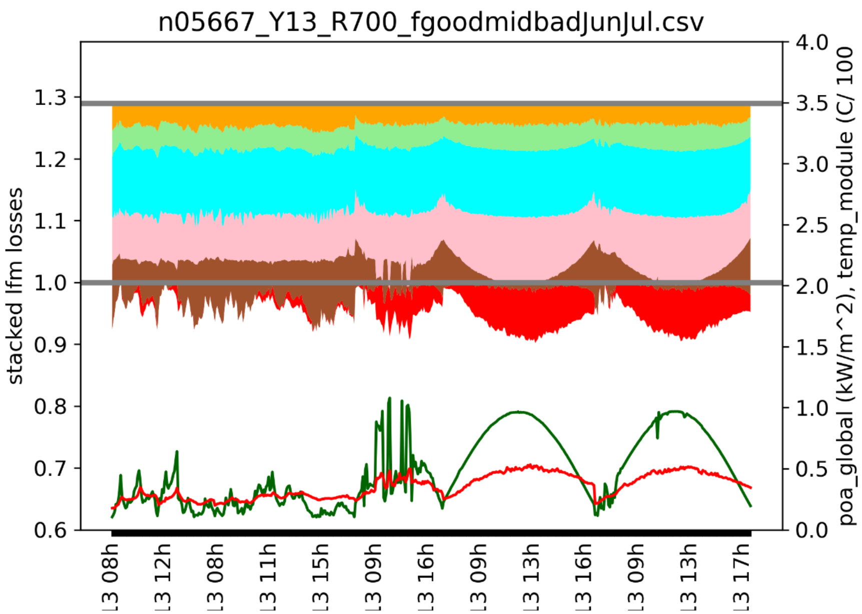
(no correction for reflectivity or spectral response from pyranometer)



Stacked losses under different weather conditions

– self referenced so easier to quantify other losses without i_sc errors

HIT 2010



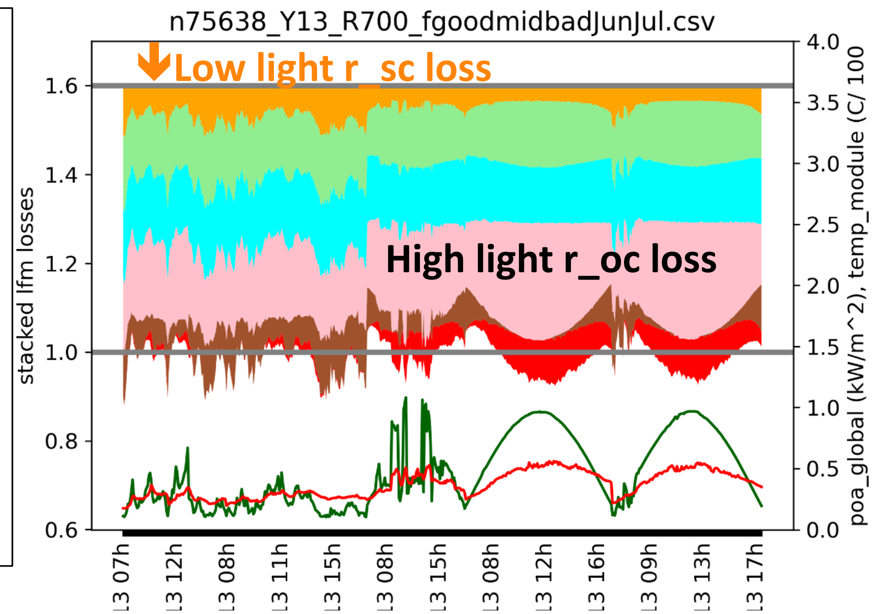
3Cloudy 1Variable 2Sunny

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

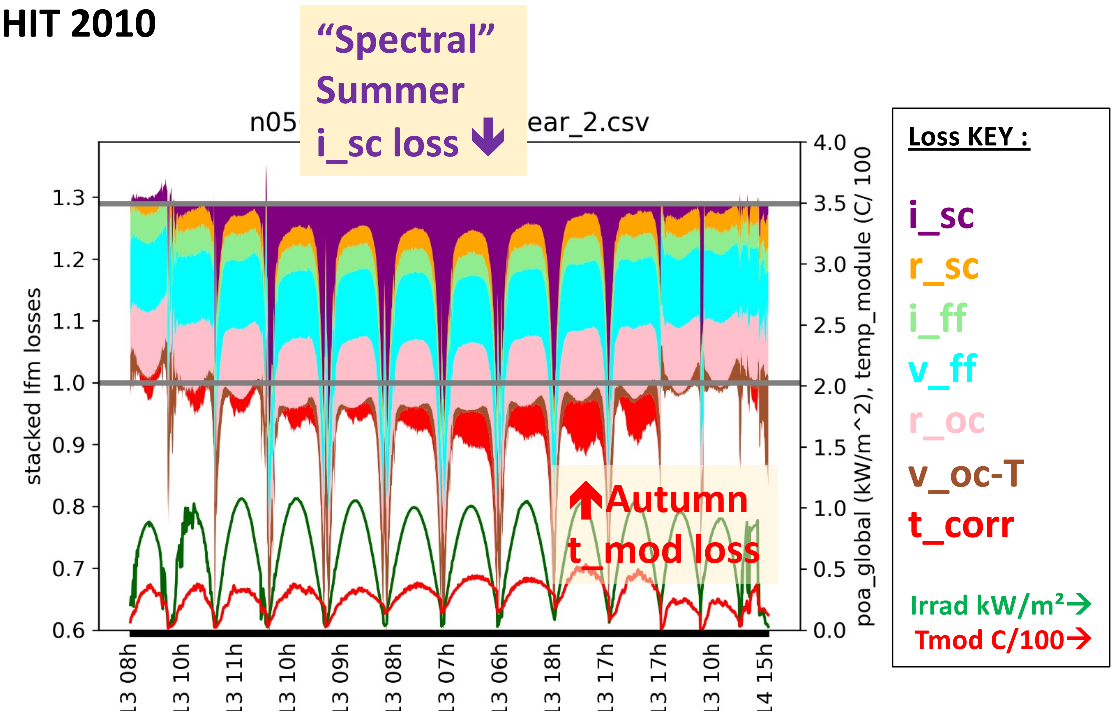


3Cloudy 1Variable 2Sunny

Stacked losses “clearest day per month Dec – Dec” “stable modules”

- can show stepwise or continuous changes, seasonal astability or maybe sensor problems

HIT 2010



Clearest day per month

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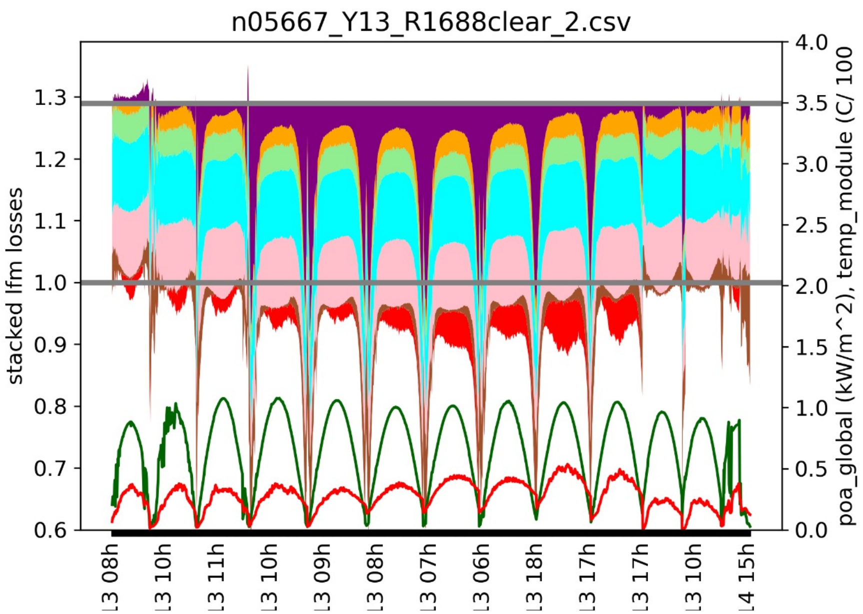
HIT 2010



Clearest day per month

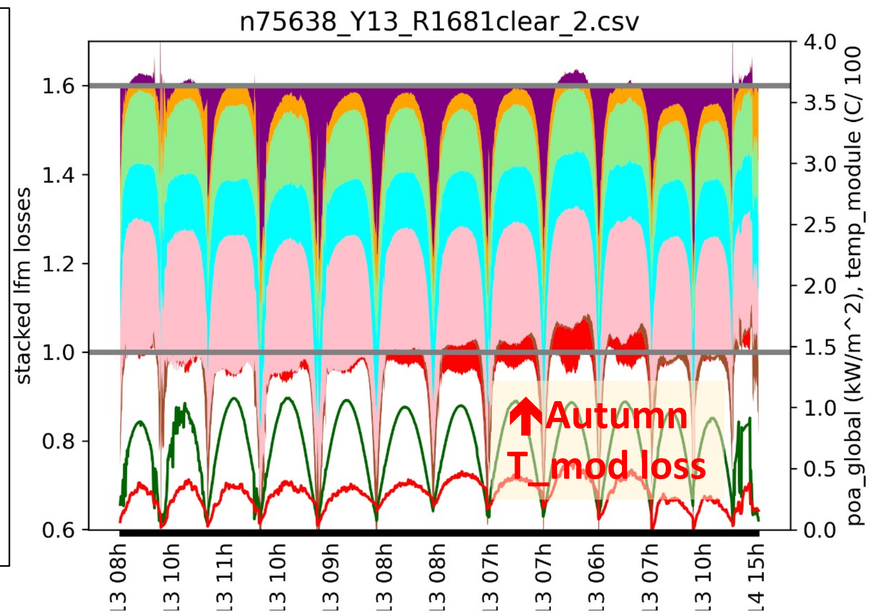
Loss KEY :

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

Irrad kW/m²→

Tmod C/100→

CdTe 2010



Clearest day per month

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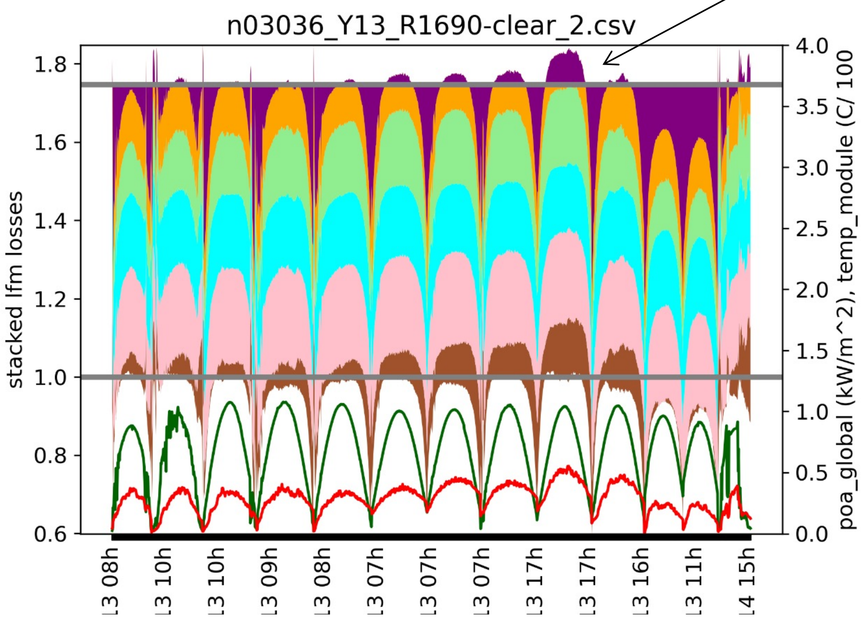
Stacked losses "clearest day per month Dec – Dec" "unstable modules"

- show changes, seasonal astability, thermal annealing or maybe sensor problems

Atypical weather days? Thermal annealing? Spectrum?
Soiling or sensor problems? i_sc worse but v_oc is better than other days

CIGS? 2010 Missing beta_v_oc



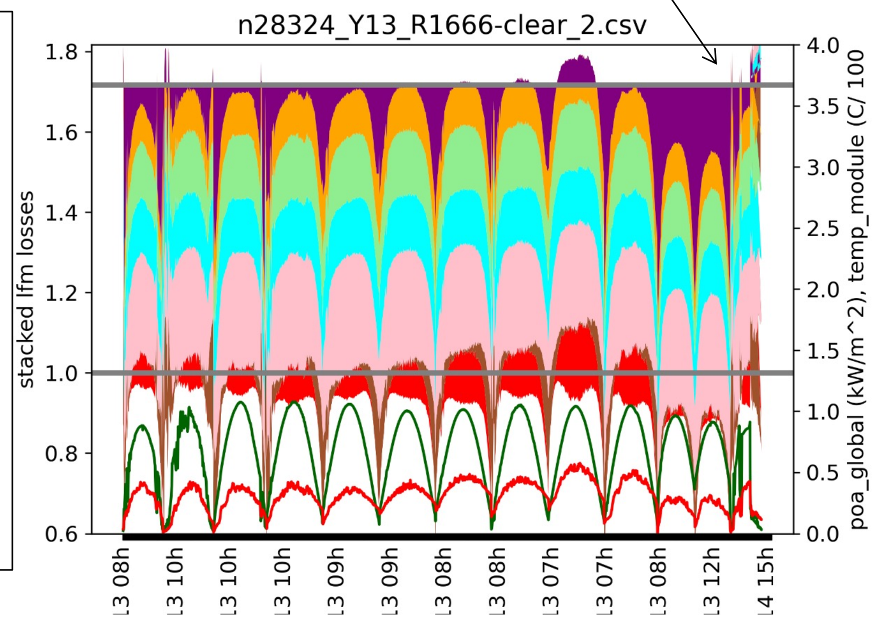
Clearest day per month

Loss KEY :

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

Irrad kW/m²→
Tmod C/100→

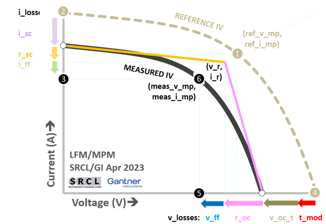
3J aSi? 2010 Beta_v_oc



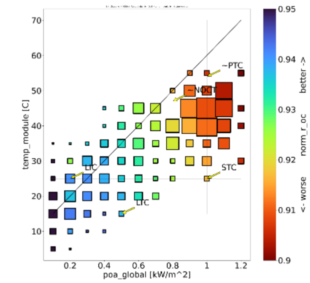
Clearest day per month

Conclusions

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

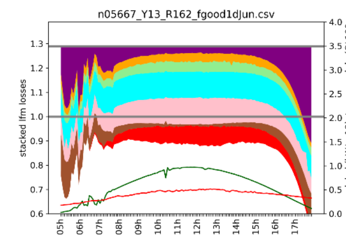


Matrix plots (with areas ~ Insolation) are easiest to visualize and fit

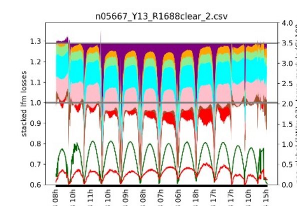


Losses and causes help understand the behaviour vs. G,T and time

Relative performance of different PV technologies has been contrasted



Please contact me for more information steve@steveransome.com



Thank you for your attention!

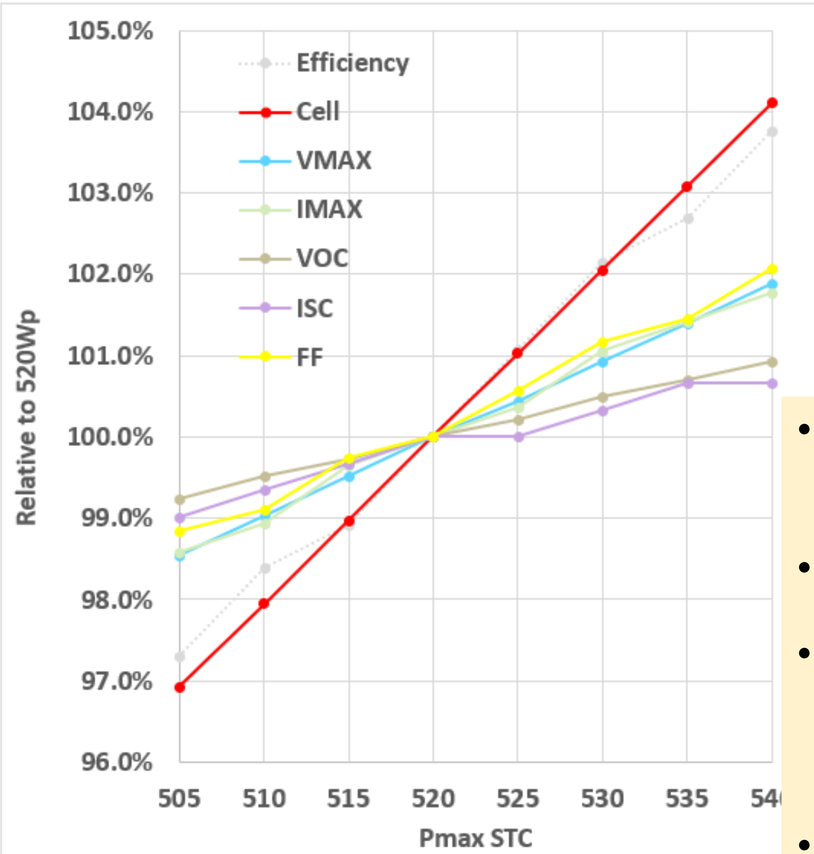
Link to temporary version until it's published bu SANDIA

www.steveransome.com/pvpmc23.pdf

- SPARE

Why it's better to use normalised fit coefficients rather than measured

https://www.firstsolar.com/-/media/First-Solar/Technical-Documents/Series-7/Series-7-TR1-Datasheet.ashx



'PES: FS-7XXXA-TR1 (XXX = NOMINAL POWER) RATINGS AT STANDARD TEST CONDITIONS (1000W/m2 , AM 1.5, 25°C)2 Nom

TYPES:	FS-7XXXA (XXX		=	NOMINAl POWER)							
AT	STANDAR TEST		CONDITIC (1000W/m2								
AM	1.5,	25°C)2									
Power3	(-0/+5%)	PMAX	(W)	505	510	515	520	525	530	535	540
		Efficiency	%	18.1	18.3	18.4	18.6	18.8	19	19.1	19.3
		Cell	%	18.9	19.1	19.3	19.5	19.7	19.9	20.1	20.3
		VMAX	(V)	182.5	183.4	184.3	185.2	186	186.9	187.8	188.7
		IMAX	(A)	2.77	2.78	2.8	2.81	2.82	2.84	2.85	2.86
		VOC	(V)	223.9	224.5	225	225.6	226.1	226.7	227.2	227.7
		ISC	(A)	3.01	3.02	3.03	3.04	3.04	3.05	3.06	3.06
				100.10%	99.97%	100.20%	100.08%	99.91%	100.15%	100.04%	99.94%

- **PV production modules are put in power bins, e.g. First Solar with 8 bins from 505-540Wp.**
- **These have steadily increasing i_sc, i_mp, v_mp and v_oc**
- **One normalised coefficient algorithm can be fitted to all bins then extrapolated to new bins rather than needing separate coefficients each bin.**
- **Normalised coeffs are in a narrow range, so are easy to check.**

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IEC 61853 1-4 : https://webstore.iec.ch/publication/6035

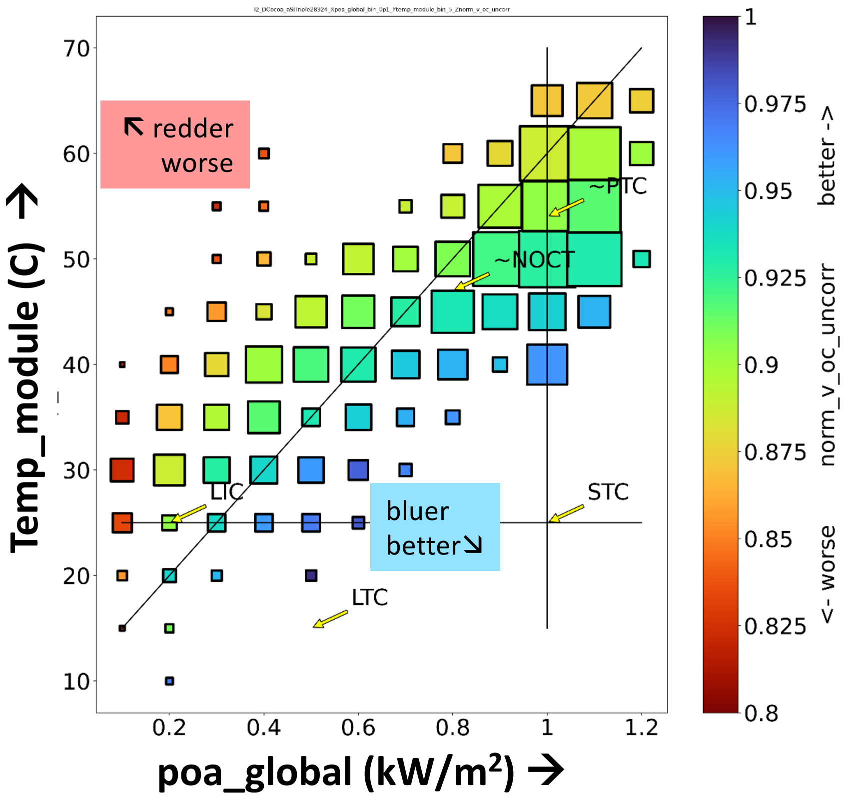
MPM 1 : "Accurate module performance characterisation using novel outdoor matrix methods PVSC-48, 2021" http://www.steveransome.com/PUBS/2021_06_PVSC48_Florida_Ransome_210617t10_submitted.pdf%20VIRTUAL%20PVSC%2048%202021

MPM 2 : "Checking the new IEC 61853.1-4 with high quality 3rd party data to benchmark its practical relevance in energy yield prediction" PVSC-46, 2019" http://www.steveransome.com/PUBS/1906_PVSC46_Chicago_Ransome.pdf

1-diode : W. De Soto et al., "Improvement and validation of a model for photovoltaic array performance", Solar Energy, vol 80, pp. 78-88, (2006)

PVPMC : Holmgren, W. C. Hansen and M. Mikofski (2018).
"pvlib Python: A python package for modeling solar energy systems." Journal of Open Source Software 3(29):884.
https://www.researchgate.net/publication/327525177_pvlib_python_a_python_package_for_modeling_solar_energy_systems

Improved matrix performance plot (with four independent parameters)



color = chosen parameter

blue=best performance

green = middle

red=worst performance

Area of squares :

α insolation H (kWh/m^2/y)

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

Effects that determine shape of measurement matrix Module #5 c-Si

`pr_dc = meas_eff / stc_eff = meas_p_max / stc_p_max / g_kW_m2`

Performance at matrix points is dominated by 5 separate effects