How to use the Loss Factors and Mechanistic Performance Models effectively with PVPMC/PVLIB.

Steve Ransome (SRCL, UK)

www.steveransome.com mailto: steve@steveransome.com

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Acknowledgements :

Juergen Sutterlueti (Gantner Instruments)

for measurement data

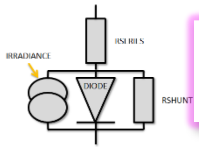
Contents of this talk

1. Introductions to Loss Factors Model and Mechanistic Performance Model (MLFM)

2. Performance and degradation analysis methods using MLFM and sample data from NREL and Gantner Instruments

3. Functionality of MLFM to be added to PVLIB python trying to fit in with their naming convention PV Modeling Glossary

1-diode model fit limitations



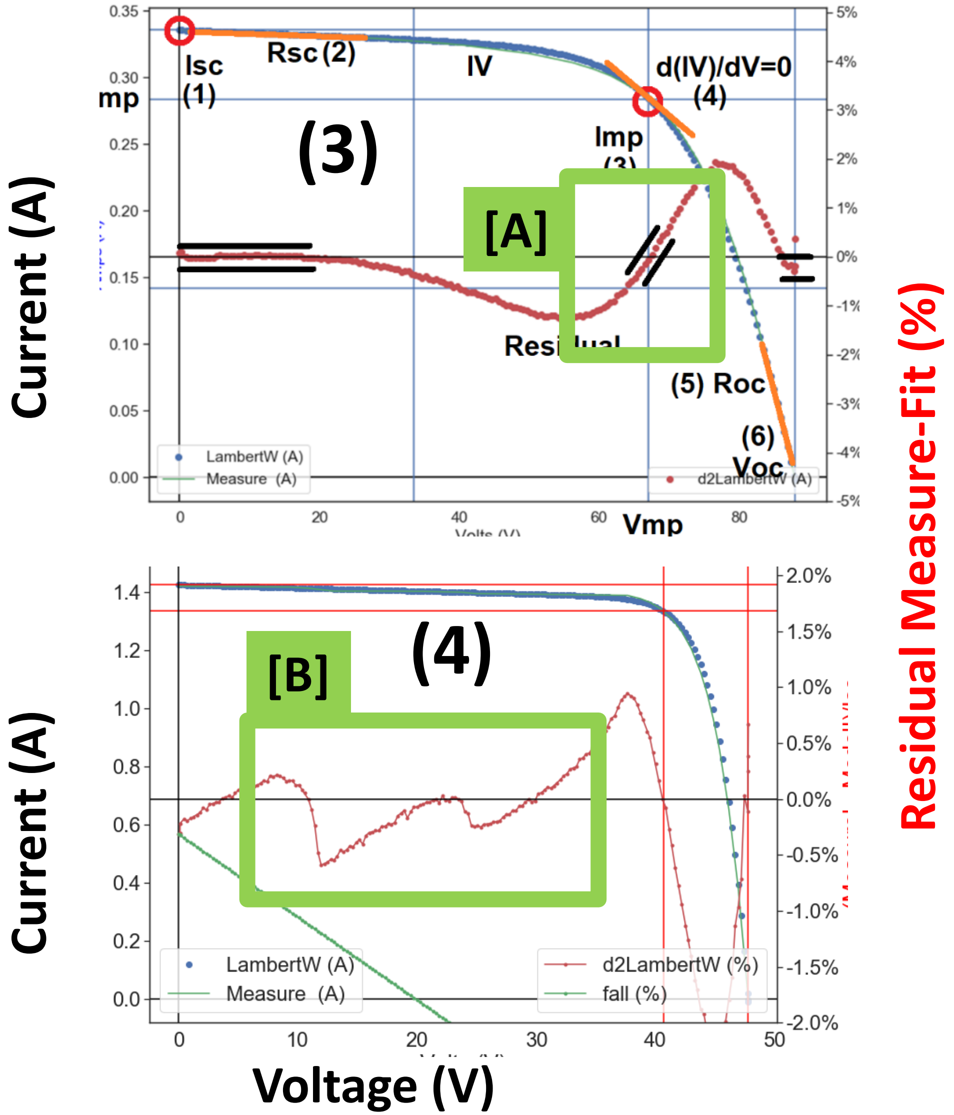
$$I = I_L - Io_1 . \exp\left(\frac{q(V+IR_s)}{nkT} - 1\right) - \frac{V+IR_s}{R_{sh}}$$

1. The 1-diode model doesn’t always fit measured IV curves well – there are 6 knowns but 5 coefficients

2. Assumptions need to be made on how I_{01} varies with temperature and R_{SHUNT} with irradiance otherwise predicted low light performance and temperature coefficients may be wrong

3. <u>Imperfect fit to smooth IV curve</u>
   Residual fits 5 knowns but has wrong slope @V=Vmp (<2% error) [A]

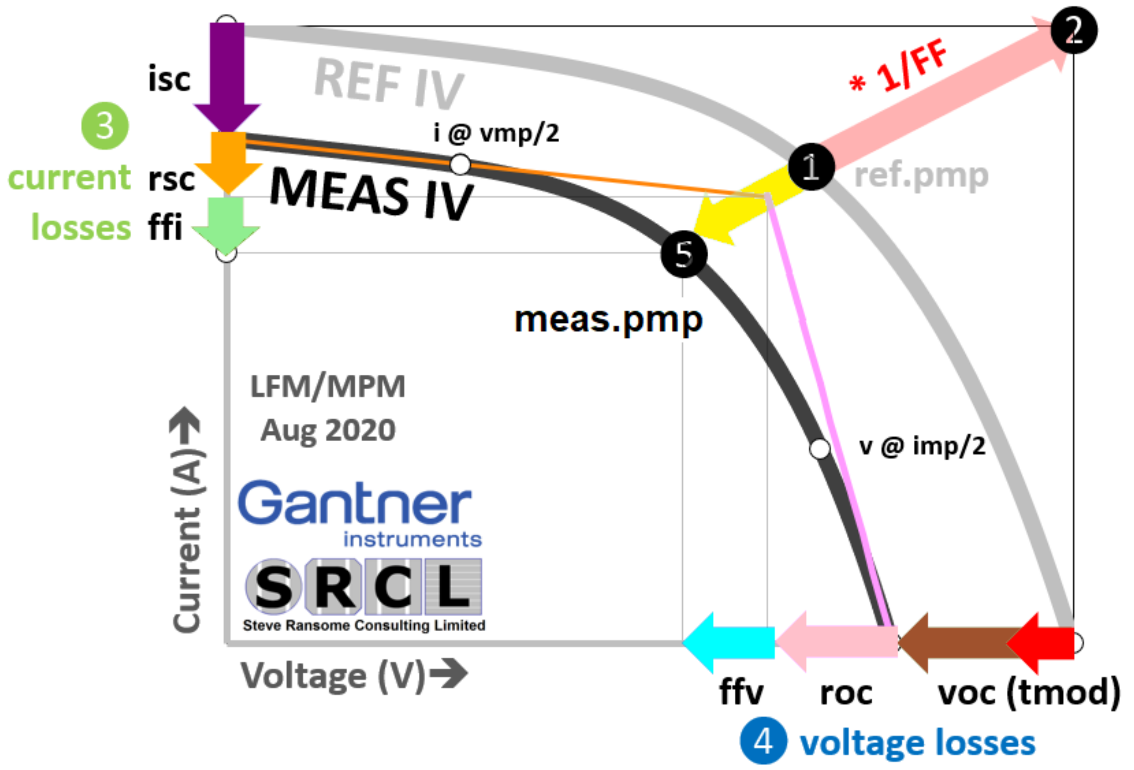
4. <u>Imperfect fit to IV with mismatch</u>
   Residual has oscillations so loss of information on mismatch [B] and fitted R_{SHUNT} value lower than expected



Loss Factors Model - area and technology independent

"Extracting normalised independent losses from the shapes of IV curves"

PRdc = 1/FF_ref * norm[(isc * rsc * ffi) * (ffv * roc * voc_Tcorr * t_mod)] <1>



1 Normalise IV curve currents and voltages by datasheet STC values so ref.imp.norm = 1 and ref.vmp.norm =1

2 Multiply by 1/FF_ref to get to isc*voc

3 Find Current losses ref.isc → meas.imp

4 Find Voltage losses ref.voc → meas.vmp

5 PR_{DC} (= meas.pmp/ref.pmp/gi)

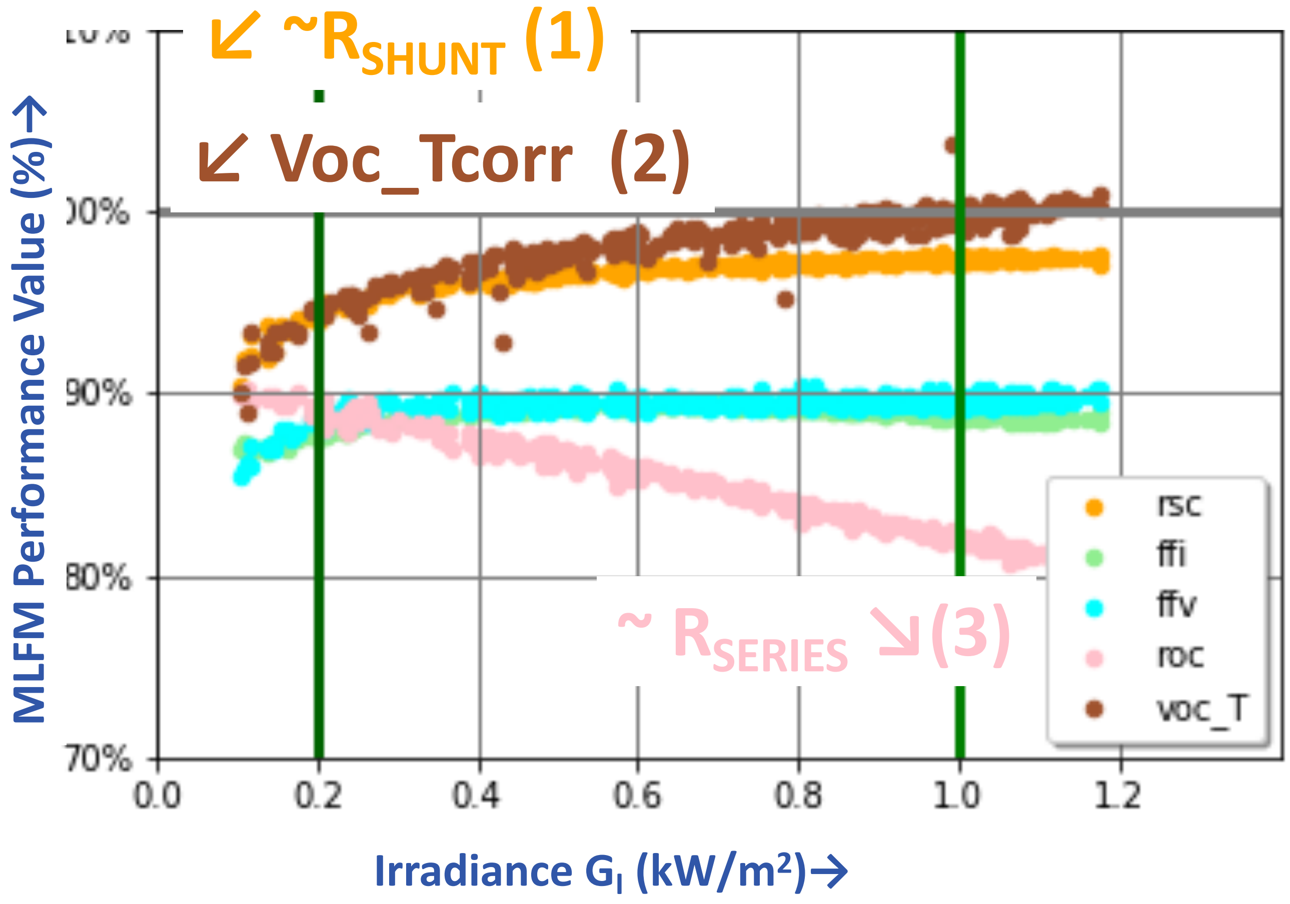
Any changes with time show degradation and cause

- Some definitions updated since the original LFM paper in 2011 EUPVSEC Hamburg.
- Naming convention in PV Modelling Glossary
- For more information on spectral and reflectivity corrections not covered here PVSC46_Chicago.pdf

LFM curves vs. irradiance identify performance limits

(NREL CdTe 1 year)

PRdc ∝ 1/FF_ref * norm[(isc * rsc * ffi) * (ffv * roc * voc_Tcorr * t_mod)] <2>



If we don't have soiling, spectral and aoi corrections for isc we can self reference.

PRdc is then proportional to the product of the remaining LFM coefficients

The 3 coefficients shown mainly determine the shape of PRdc vs. irradiance

Mechanistic Performance Model –location and technology independent

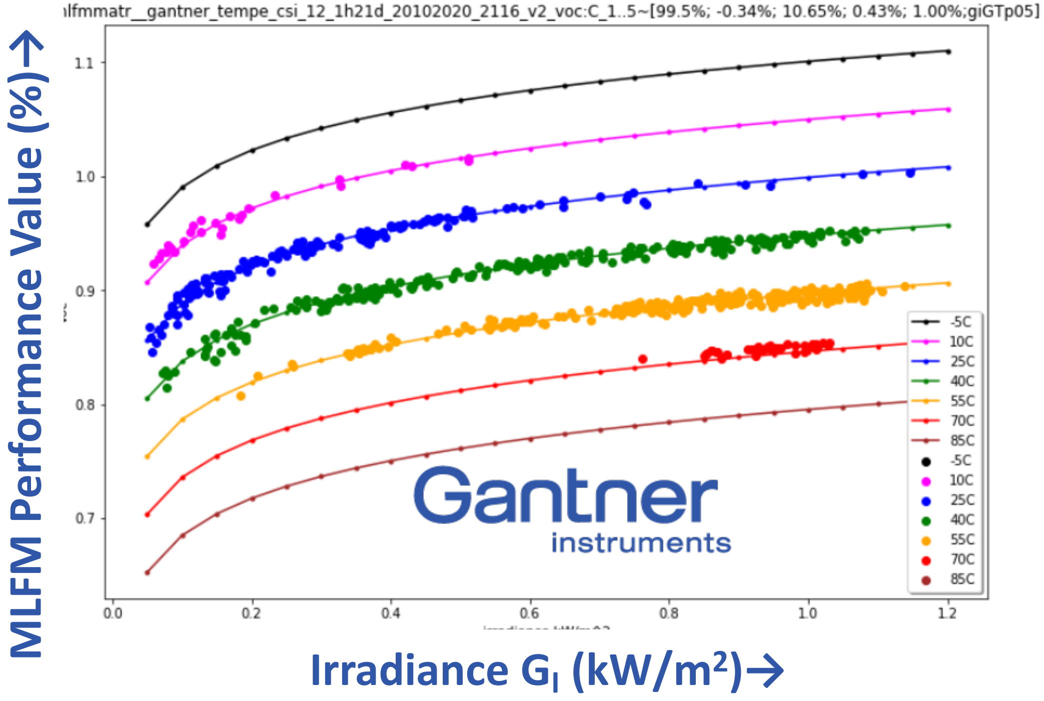
"Fits PV performance vs. irradiance and temperature with robust coefficients"

$$\mathbf{MPM:} \quad = C_1 + C_2 \times (T_{MOD} - 25) + C_3 \times \mathrm{Log}_{10}(G_I) + C_4 \times G_I + \cdots \qquad \text{<3>}$$

- C_1 = **Tolerance** = (meas/ref)
- C_2 = **Temperature coefficient** (e.g. gamma_pmp ~ -0.4%/K)
- C_3 = **low light loss** (caused by $Voc(G_I)$)
- C_4 = **high light loss** (caused by R_{SERIES})
- **Optional extra coefficients IF NEEDED** C_5= WS, C_6=some modules R_{SHUNT} C_X = Beam Fraction/AOI, Spectral, non-linearity
- **Degradation studies** – quantify changes with coefficients over time
- **Fault finding** – coefficients that glitch or aren't expected values
-

PVPVC 2017 Canobbio paper

Reference : PVSC46_Chicago.pdf



Predicted (lines) vs. Measured (dots)
LFM values fitted with MPM
(7 years cSi module in Tempe AZ)

Improving the understanding of loss parameters

Translate “multiplying losses” to “stacked (subtracting) losses” for better visualisation

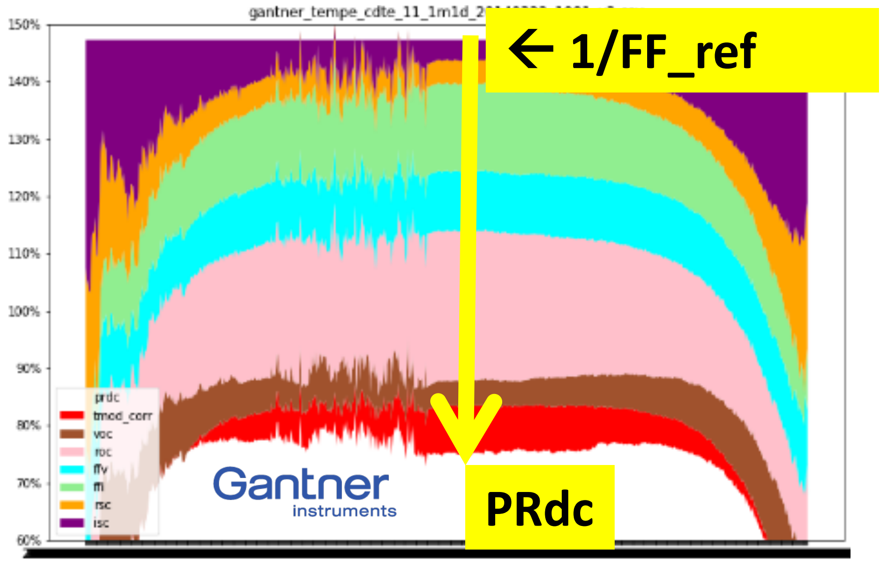
Product (e.g. “* 0.98 * 0.95 * 0.97”)

PRdc = 1/FF_ref * norm[(isc * rsc * ffi) * (ffv * roc * voc_Tcorr * t_mod)] <1>

Sum (e.g. “–0.02 -0.05 –0.03”)

PRdc = 1/FF_ref – stacked_loss[(isc + rsc + ffi) + (ffv + roc + voc_Tcorr + t_mod)] <4>

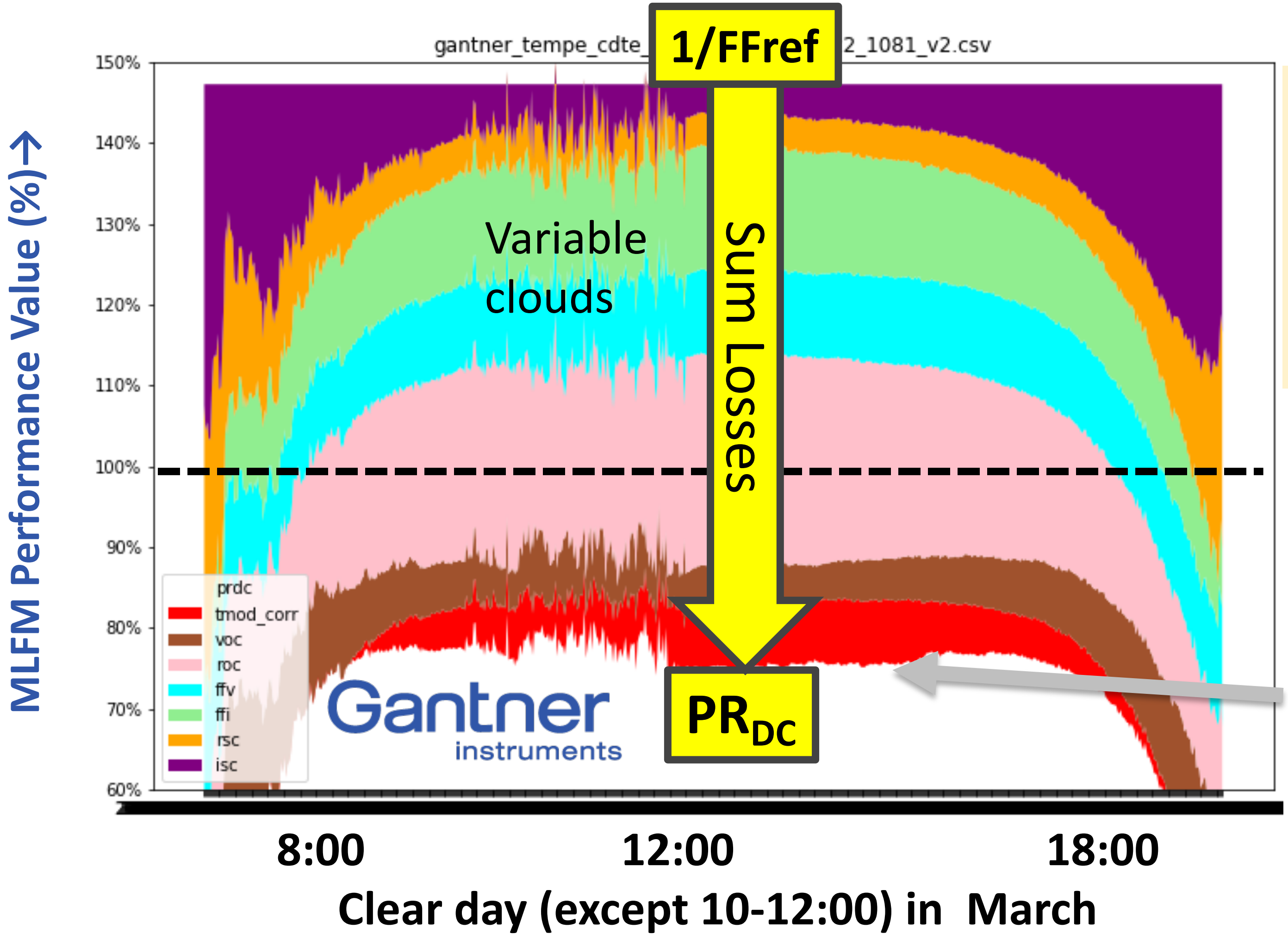
Need a scaling factor to make sure start and stop points are correct



Looking at stacked losses vs. time : 1 day

CdTe : Clear day in March, Tempe AZ

PRdc = 1/FF_ref – stacked_loss[(isc + rsc + ffi) + (ffv + roc + voc_Tcorr + t_mod)] <4>



Tallest colour bands = Highest losses

For this module :
There's more ~Rseries than ~Rshunt loss (thin film)

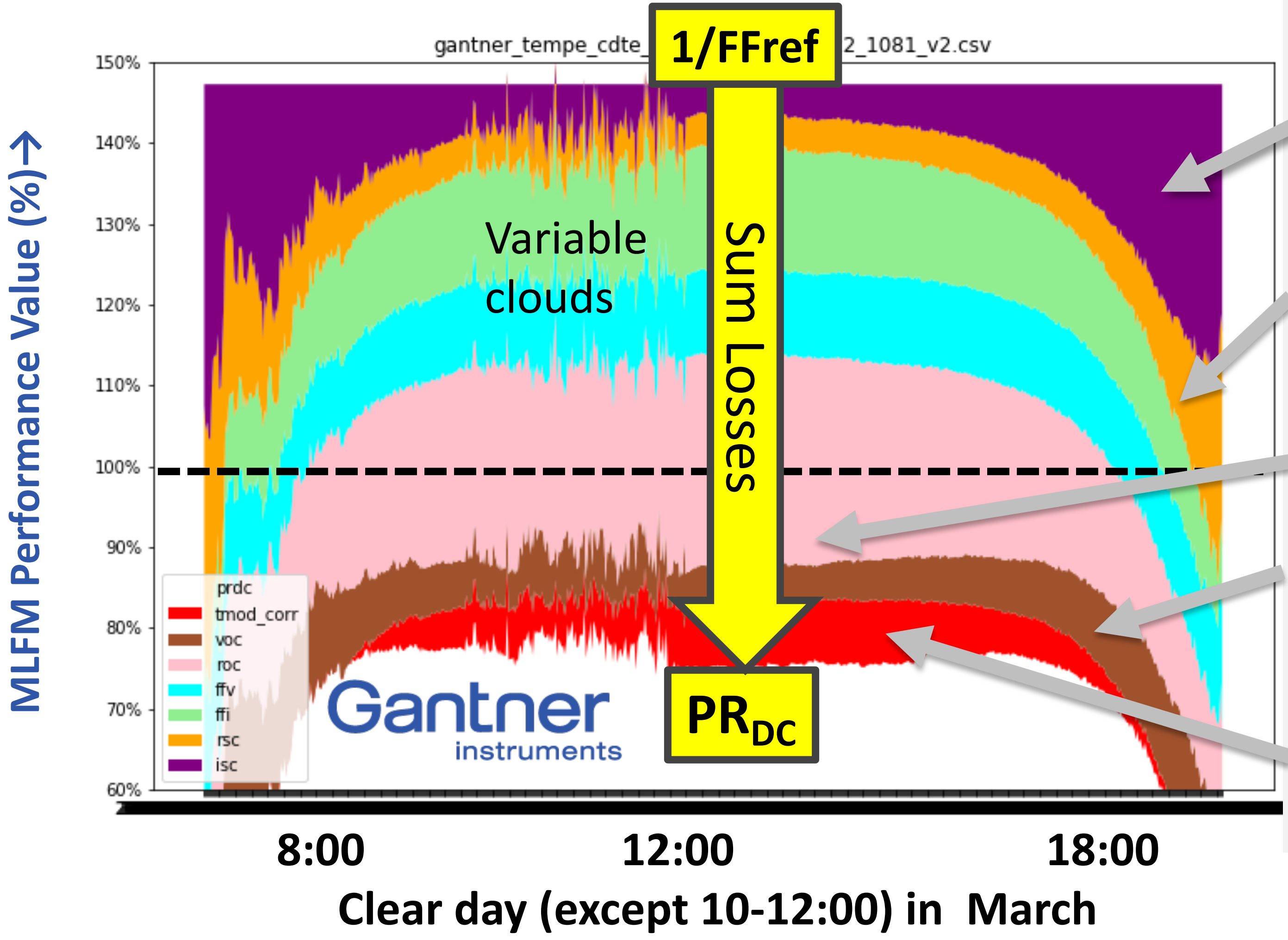
100%

← Explain shape of PRdc vs. time

Stacked losses vs. time : 1 day

CdTe : Clear day in March, Tempe AZ

PRdc = 1/FFref – stacked_loss[(isc + rsc + ffi) + (ffv + roc + voc_Tcorr + t_mod)]   <4>



When are losses greatest?

(1) Isc loss (aoi/reflectivity, spectrum)→ morning, evening

(2) ~Rshunt loss (low irradiance) → morning, evening

(3) ~Rseries loss (high I^2.Rseries) → noon

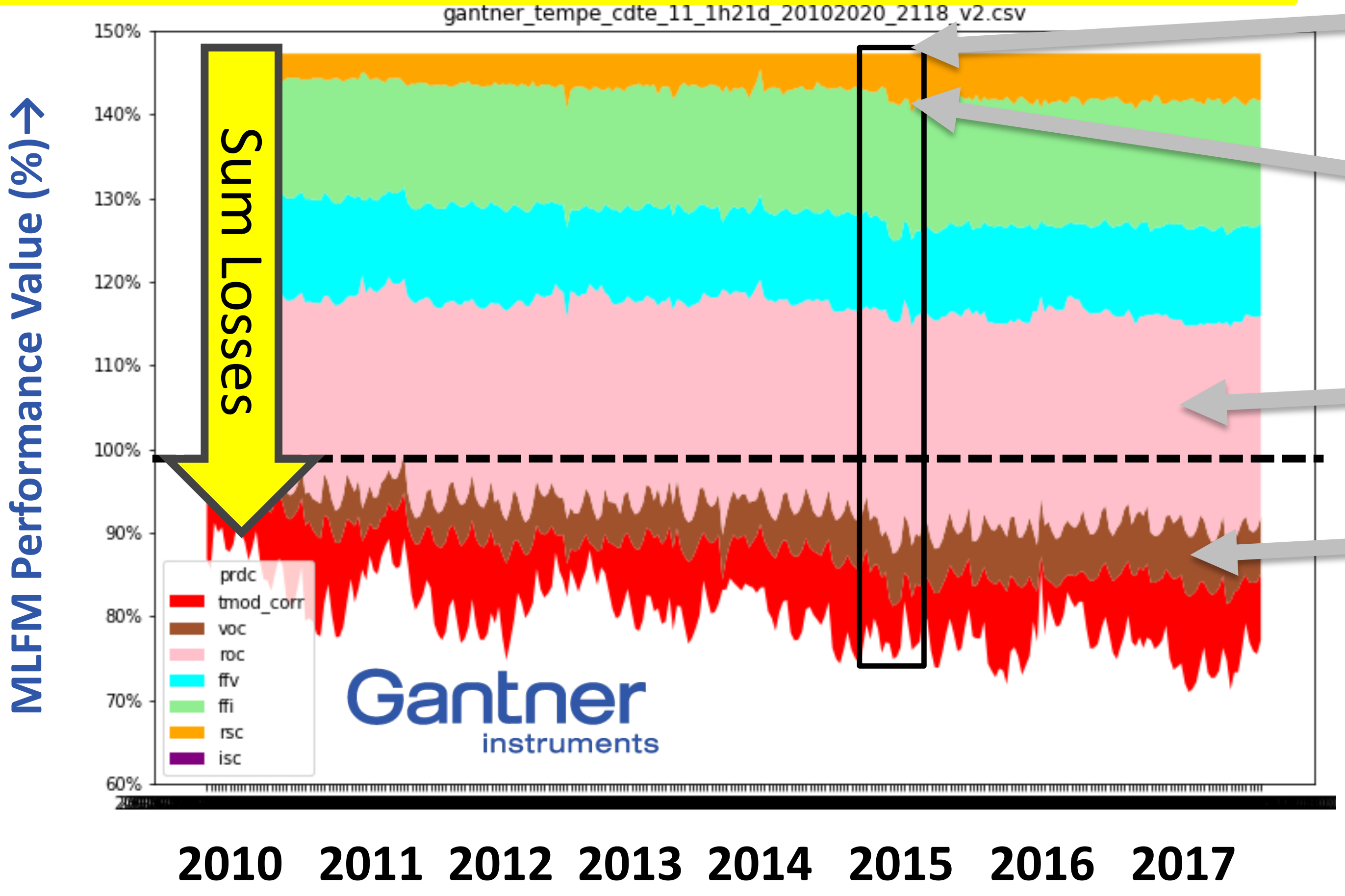
(4) Voc_tcorr (temp_corrected) (Voc~log(Gi) → low irradiance

(5) Temperature loss → noon - afternoon (high temperature)

Stacked losses vs. time – 7 Years degrading module

CdTe : March, Tempe AZ. Gi > 0.75 SHOWN FOR CLARITY, 1day/month. Self referenced

PRdc ∝ 1/FFref – stacked_loss[(~~isc~~ + rsc + ffi) + (ffv + roc + voc_Tcorr + t_mod)] <5>



7 years data

(1) A step change happened in 2015

(2) ~Rshunt worsened → 2015

(3) ~Rseries → Worsening over time

(4) Voc_Tcorr → worsening with time

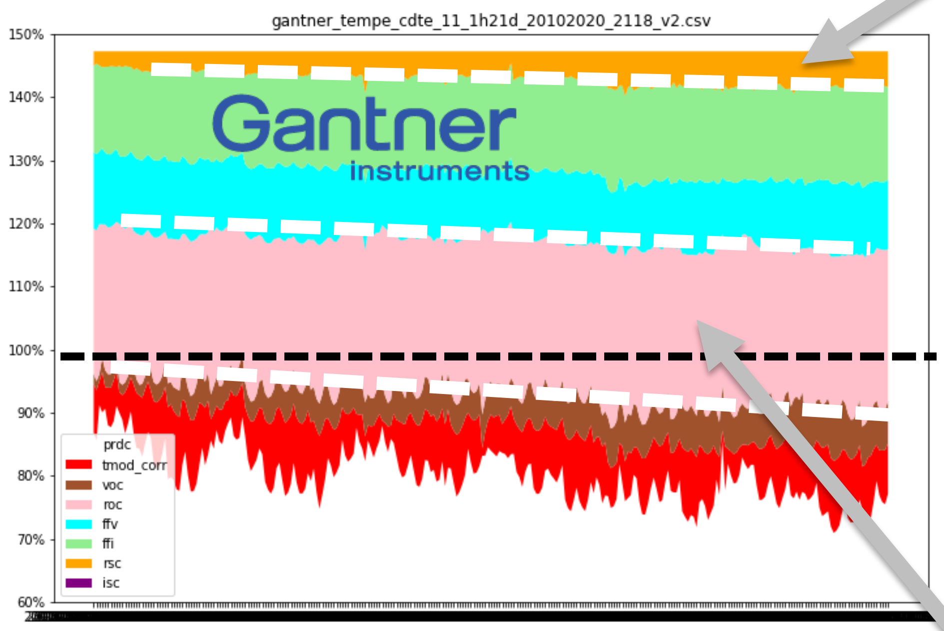
(5) Temperature loss →seasonal

Stacked loss graphs identify any long-term degradation –

Gantner 2010-2017+ (self referenced Isc) Unstable

PRdc ∝ 1/FF_ref – stacked_loss[(~~isc~~ + rsc + ffi) + (ffv + roc + voc_Tcorr + t_mod)] <5>

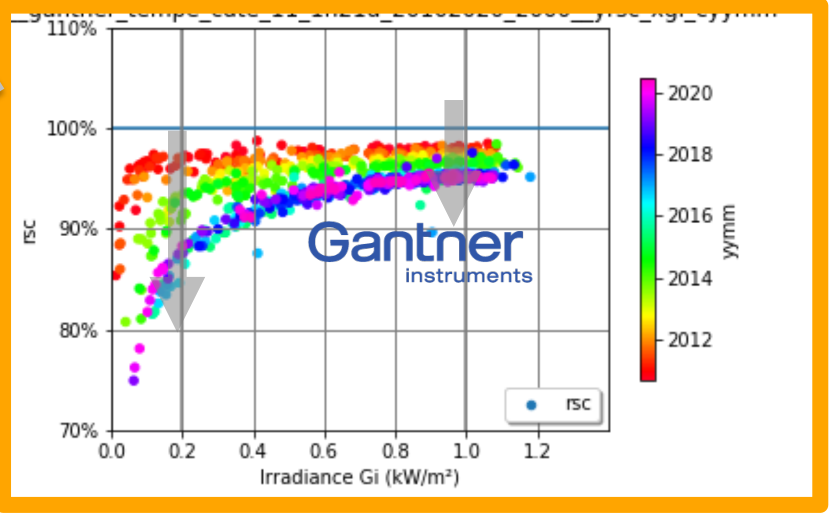
Performance →



2010 2011 2012 2013 2014 2015 2016 2017

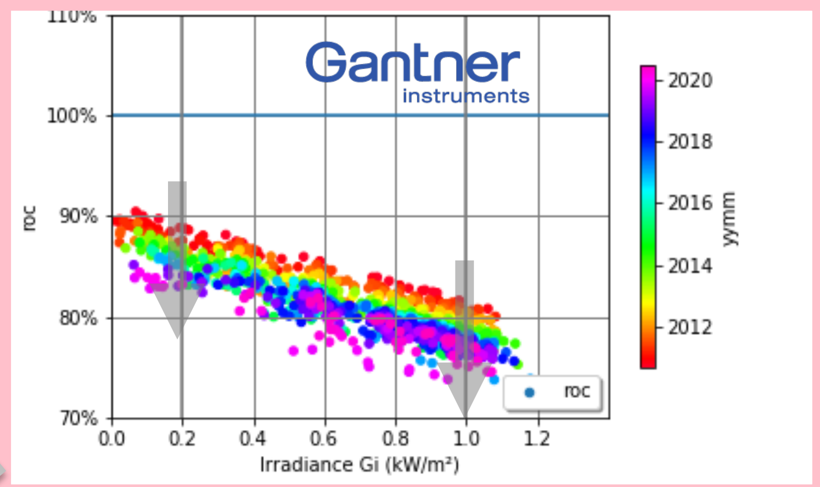
Rsc
FFi
FFv
Roc
Voc
Tmod
PRdc

(1) ~Rshunt



(2) ~Rseries

Irradiance G_I (kW/m²)→



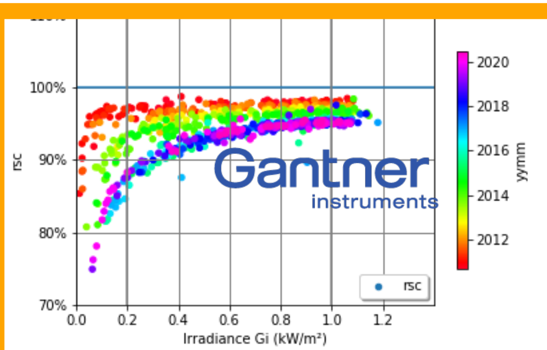
Degradation : identifying the cause and quantifying rates

$$\text{MPM}: \quad = C_1 + C_2 \times (T_{MOD} - 25) + C_3 \times \text{Log}_{10}(G_I) + C_4 \times G_I + \cdots$$ <3>

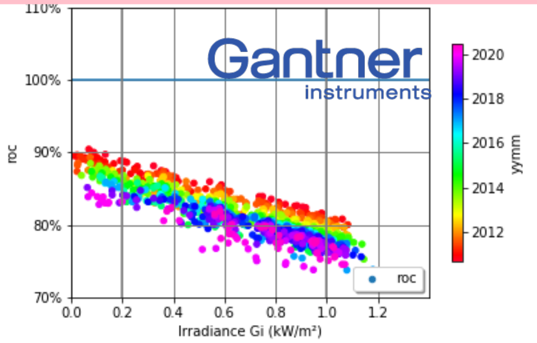
Excel analysis of fitted MPM coefficients exported as csv

Years	mlfm	Tolerance "c_1"	Temp Coeff "c_2"	LowLight (Voc, Rsh) "c_3"	HighLight (Rs) "c_4"	0.2kW/m² 25C LIC	1.0kW/m² 25C STC
2010-13	rsc	100.2%	0.0%	5.6%	-2.4%	95.8%	97.8%
2013-17	rsc	100.2%	0.0%	13.2%	-5.1%	90.0%	95.2%
2017-20+	rsc	103.3%	0.0%	20.8%	-8.4%	87.1%	94.9%
2010-13	roc	89.0%	0.0%	-0.6%	-10.3%	87.3%	78.6%
2013-17	roc	85.9%	0.1%	-2.1%	-9.8%	85.4%	76.1%
2017-20+	roc	86.5%	0.1%	0.4%	-12.0%	83.8%	74.4%

(1) ~Rshunt
Higher loss at LIC (-9%)
than STC (-3%)

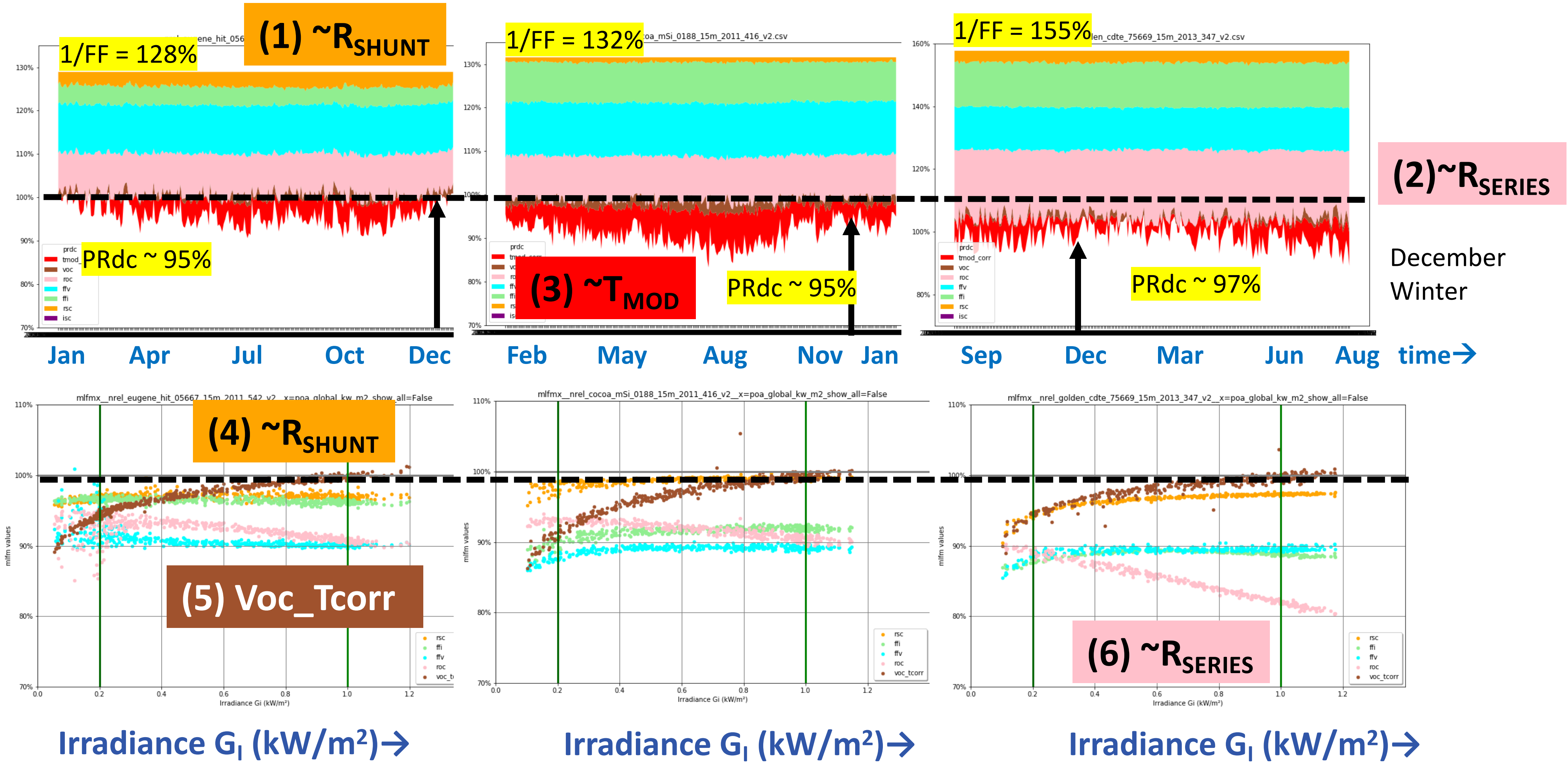


(2) ~Rseries
Similar loss 3-4% at
LIC and STC



Distinguishing technologies by time(top) or irradiance (bottom)

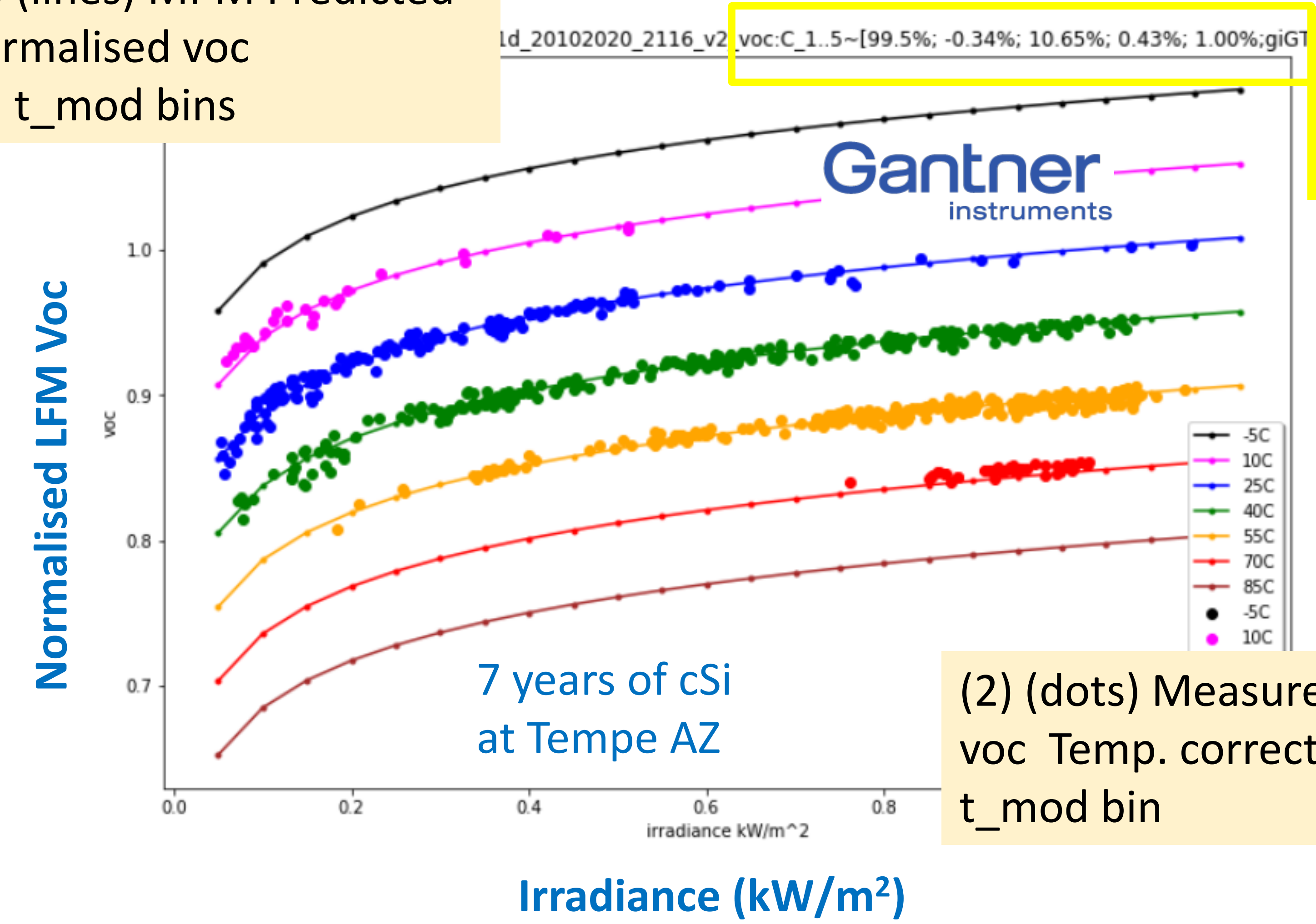
Eugene HIT 01/2013 to 12/2013 | Cocoa mSi 02/2011 to 01/2012 | Golden CdTe 09/2012 to 08/2013 | NREL



Measured vs. Predicted performance vs. irradiance and temperature bins (coloured dots) works for any LFM parameters

(1) (lines) MPM Predicted normalised voc vs. t_mod bins

(3) MPM Fit coefficients beta_voc = -0.34%/K



If then module is unstable plot short durations (< 1 month) otherwise any degradation will affect fit accuracy

(2) (dots) Measured LFM normalised voc Temp. corrected to nearest t_mod bin

Adding the code to PVPMC https://github.com/DuraMAT/pv-terms/issues

- All the graphs here were generated using code to be put into PVLIB

- **Sample data to be added**
  - 3 modules at different sites for 1 year at NREL
    (although I had to calculate Rshunt and Rseries as this is not included)
  - 2 modules (1 CdTe, 1 cSi) from Gantner instruments
    Frequent data on a clear day March, and 7 years of hourly data
- **Code includes**
  - reference, measurement → normalised → stack loss dataframes
  - Fit algorithms
  - 5+ graphs

MLFM program sections and sample graphs

1. Get user choice of module measurement data and reference values
2. Get which LFM parameter to analyse and plot e.g. PRdc, voc …
3. Get xaxis (Gi, Tmod, datetime) to analyse mlfm and plot for fig 1
4. Get xaxis and colour axis (Gi, Tmod, datetime) for fig 2
5. Calculate normalised mlfm from measured and reference values
6. Filter and Erase outliers (much easier with normalised data)
7. Plot many MLFM values (y axis) vs. Gi, Tmod, Datetime (Fig 1)
8. Plot MLFM vs. t_module, irradiance, datetime with colours (Fig 2)
9. Transform form multiplicative MLFM losses to a subtractive stacked chart format
10. Plot stack losses from 1/FF down to PRdc vs. time (Fig 3)
11. MPM curve fit to selected LFM parameter – store coeffs to "output.csv"
12. Plot MLFM measured, fitted vs. irradiance (Fig 4)
13. Plot MLFM measured, fitted vs. irradiance and temp (Fig 5)

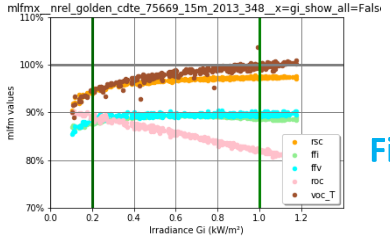


Fig 1

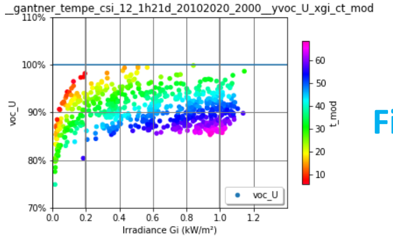


Fig 2

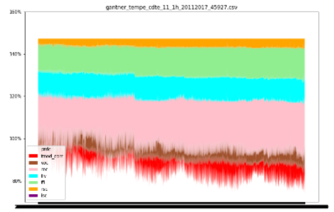


Fig 3

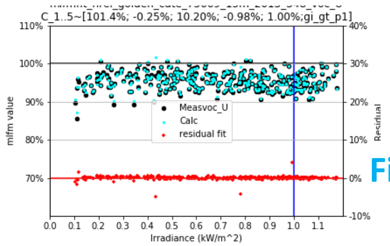


Fig 4

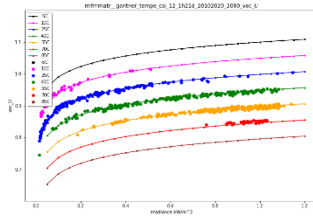


Fig 5

Gantner Instruments' OTF Solutions

Further info at otf@gantner-instruments.com or email authors

PV Modules Measurements:

Fixed and 2D track; IV curve every minute, all environmental sensors, spectral parameters
PV Module Power up to 500W/800W
High quality digitalization, current accuracy 0.1% FS, voltage: 0.05% FS
Scalable system (4 .. 48 channels) with raw data access
Local or cloud-based data streaming
Derived parameters using Loss Factors and Mechanistic Performance Models
Integrated Python Jupyter Lab for direct analysis and automatic reporting

Continuous measurements in Arizona since 2010; Other sites available around the world

Trusted by leading PV Module manufacturers, Technology providers and Research Labs

GI OTF MEASUREMENTS

Name	Description	Units
G_H	Global Horizontal Irradiance	kW/m²
D_H	Diffuse Horizontal Irradiance	kW/m²
B_N	Beam Normal Irradiance	kW/m²
G_I	Global Inclined Irradiance (Pyranometers and c-Si ref cells)	kW/m²
T_{AMB}	Ambient Temperature	C
T_{MOD}	Back of Module Temperatures	C
WS	Wind Speed	ms^{-1}
WD	Wind Direction	°
RH	Relative Humidity	%
G(λ)	Spectral Irradiance G(350– 1050nm)	W/m²/nm

Summary

- **Loss factors model** – meaningful, independent coefficient analysis of IV curve performance
- **Mechanistic Performance Model** – fits meaningful, independent coefficients to LFM/PRdc/Matrices vs. irradiance and module temperature
- **Good quality data** allows a lot of understanding better than 1-diode model
- Graphical analysis shown both multiplicative and stacked losses to find cause of any underperformance and quantify degradation
- Code will be introduced into PVLIB

- We are doing much more analysis that hasn't been covered in this short talk e.g. mismatch, spectral, aoi/beam fraction … see our previous talks.

- **Feedback welcome !**

Contact

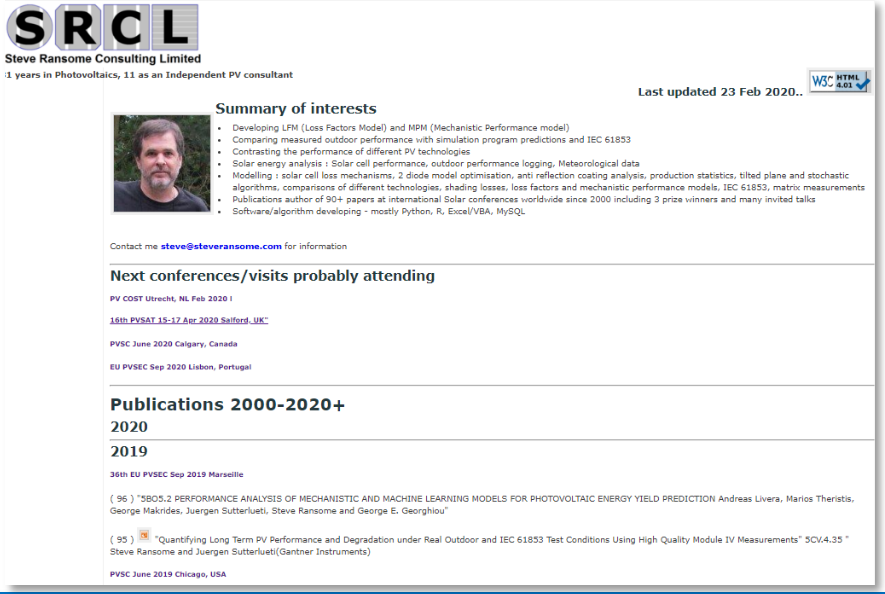
Steve Ransome (SRCL, UK) www.steveransome.com ; mailto: steve@steveransome.com

Acknowledgements: Juergen Sutterlueti (Gantner Instruments)

Contact us for OTF enquiries and high-quality data sets for your own research

www.gantner-instruments.com/products/software/gi-cloud/

Thank you for your attention



All papers are either available through SRCL website or writing to me directly

Also

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

NAMING CONVENTION https://duramat.github.io/pv-terms/

PVPMC https://pvpmc.sandia.gov/