Advanced degradation modelling – finding causes and rates

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PV Cost Webinar on PV Performance Modelling Methods:

1st Dec 2020

Acknowledgements :
Juergen Sutterlueti (Gantner Instruments)
for some measurement data and help.

Focus of talk

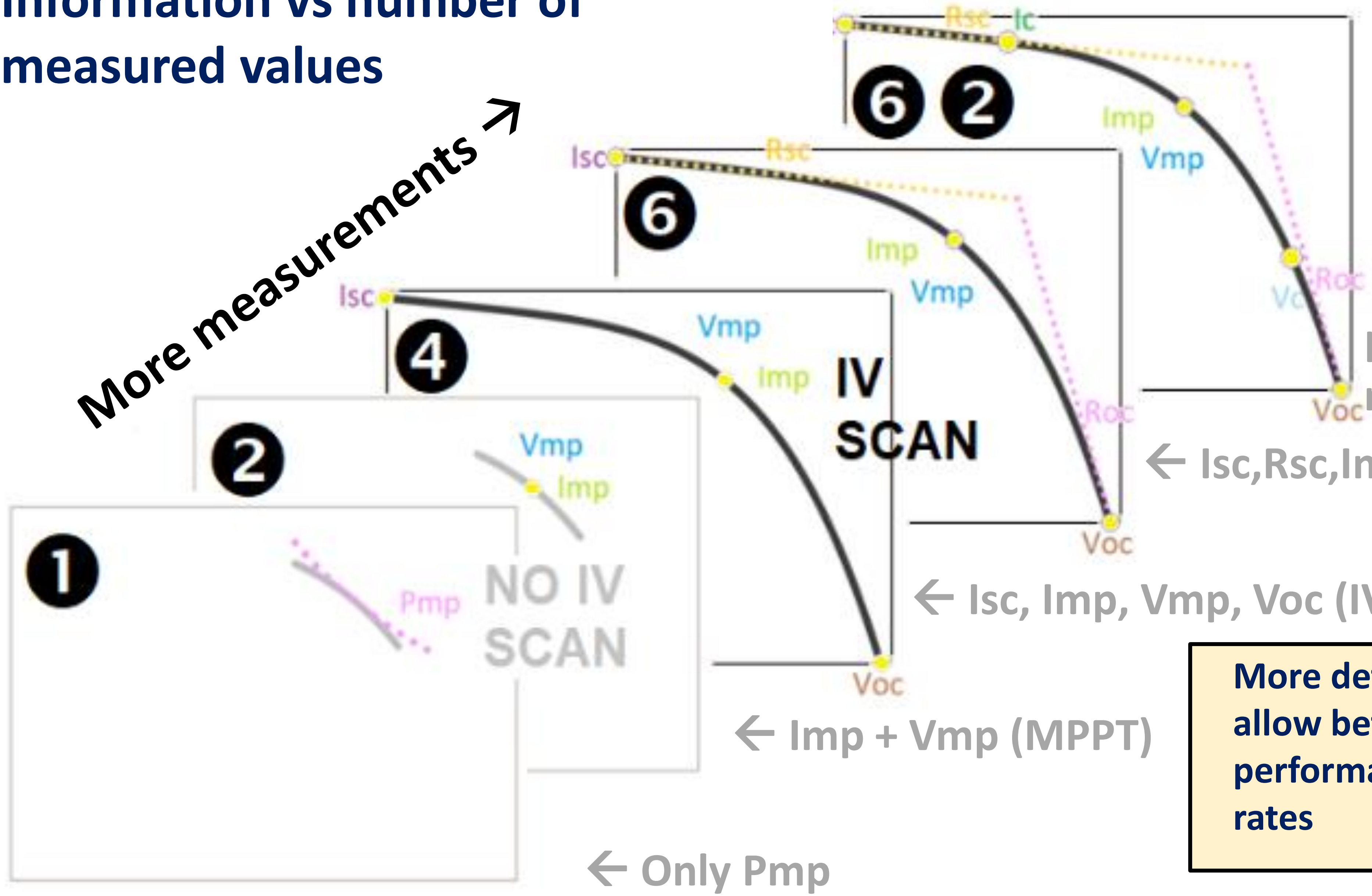
1. Many 3rd party studies report module degradation rates using performance curve fitting, linear regression, Year on Year etc.
2. These usually reporting only **Efficiency changes %/year** often from conditions either "near STC" or "corrected to STC"
3. However many different parameters that can change including I_{SC}, Fill Factor, V_{OC}, R_{SHUNT}, R_{SERIES} …
4. These changes have a non-linear effect on efficiency and energy yield
5. They affect power reduction differently under different conditions e.g.
    1. A fall in $\mathbf{R_{SHUNT}}$ will cause a <u>worse power drop at low light levels</u> and therefore a greater energy yield drop at <u>low insolation climates</u>
    2. A rise in $\mathbf{R_{SERIES}}$ gives a <u>worse power drop at high irradiance</u> which will give a larger fall under <u>sunny climates</u>

Focus of talk (continued)

1. This talk looks at methods to improve the understanding of degradation rates and causes
2. It uses normalised analysis with independent coefficients
3. Fits to the data can result in calculated degradation rates at different instantaneous conditions and energy yields at different sites

4. Most of the data presented is from Gantner Instruments' OTF in Tempe AZ but many other sites have been analysed including NREL

Information vs number of measured values



(Module temperature)

← 6 + 2 curvature parameters Ic, Vc for mismatch, and rollover

← Isc,Rsc,Imp,Vmp,Roc,Voc

← Isc, Imp, Vmp, Voc (IV SCAN)

← Imp + Vmp (MPPT)

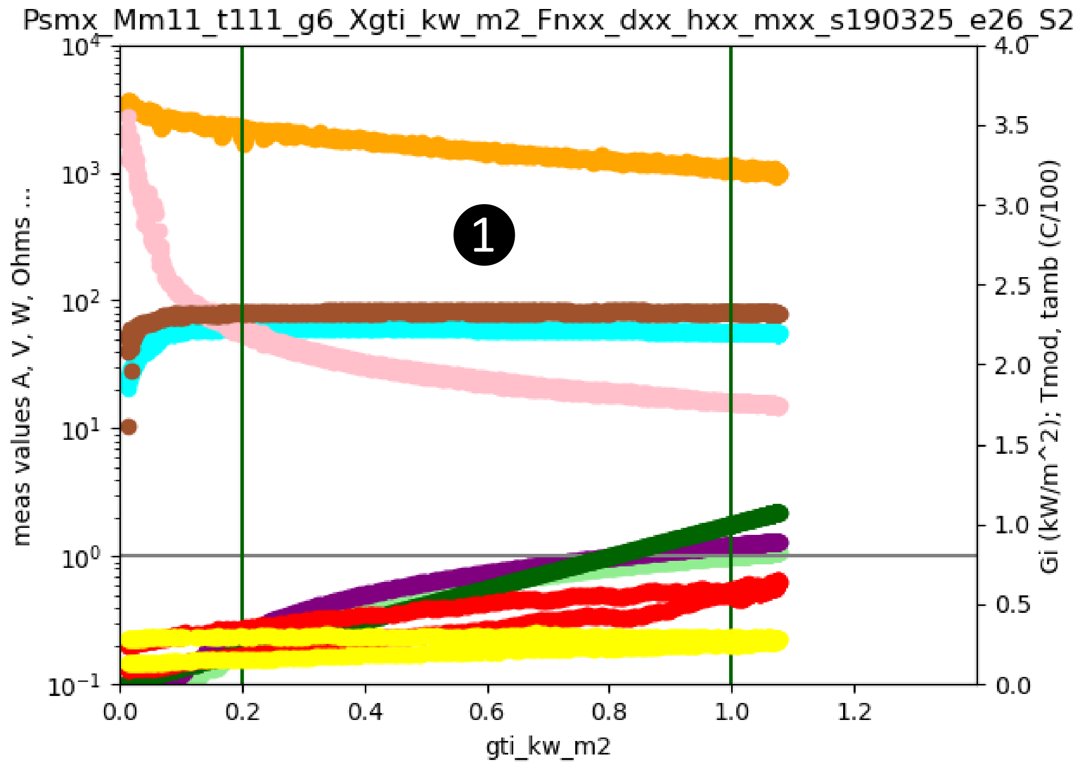
← Only Pmp

More detailed measurements allow better identification of performance causes and change rates

Measured IV parameters Isc(A) Rsc(Ohms) Imp(A) Vmp(V) Roc(Ohms) Voc(V) on a logarithmic y axis >5 orders of magnitude (10^{-1}A to 10^{4} Ohms)

Absolute values depend on module technology, cell numbers, module area, series strings etc.

#11 Thin film
Measured parameters vs. irradiance



10 000

KEY

Isc

Rsc

Imp

Vmp

Roc

Voc_tcorr

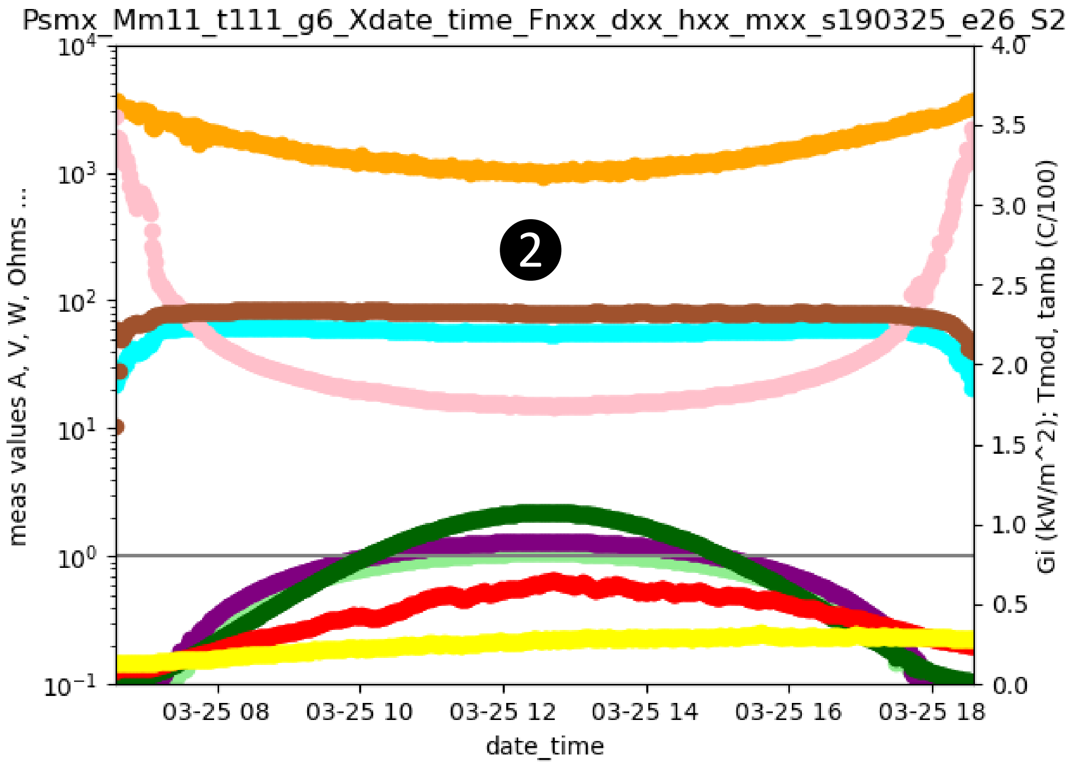
Irrad kW/m²

Tmod C/100

Tamb C/100

0.1

#11 Thin film
Measured parameters vs. datetime

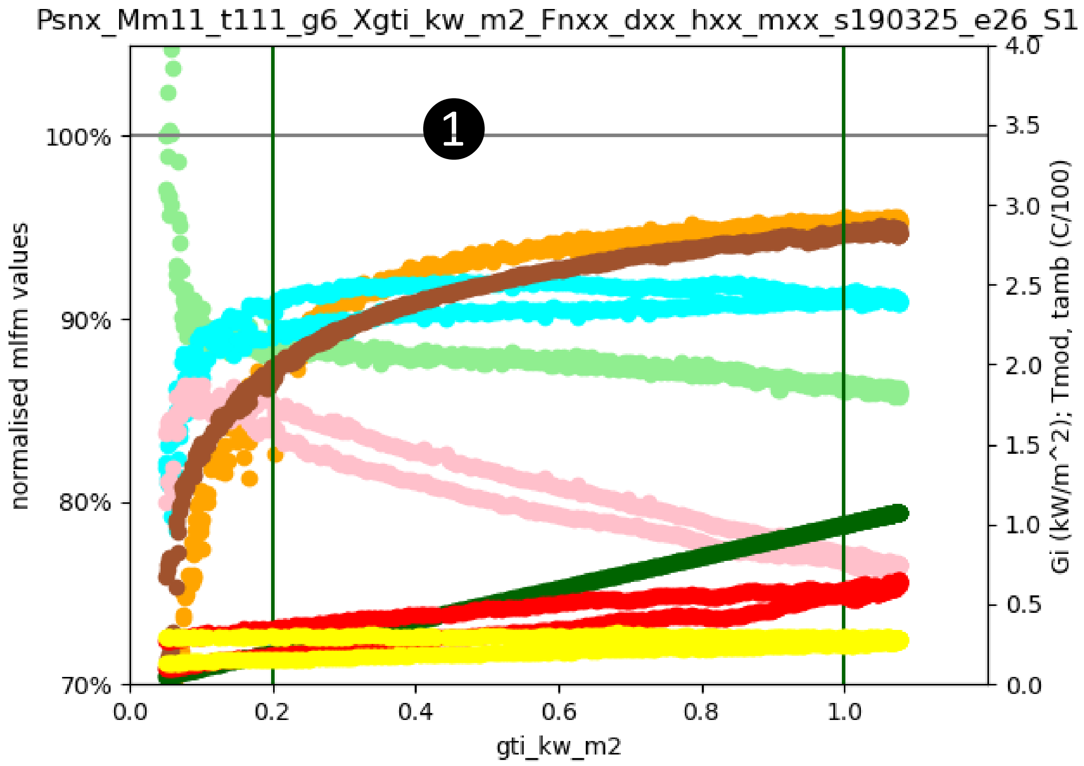


Normalised LFM parameters Isc(%) Rsc(%) FFi(%) FFv(%) Roc(%) Voc(%)

yaxis ~70-110%, easier to model, area and number of cell independent

LFM = Loss Factors Model

#11 Thin film
Normalised parameters vs. irradiance



1.05

KEY

Isc

Rsc

FFi

FFv

Roc

Voc_tcorr

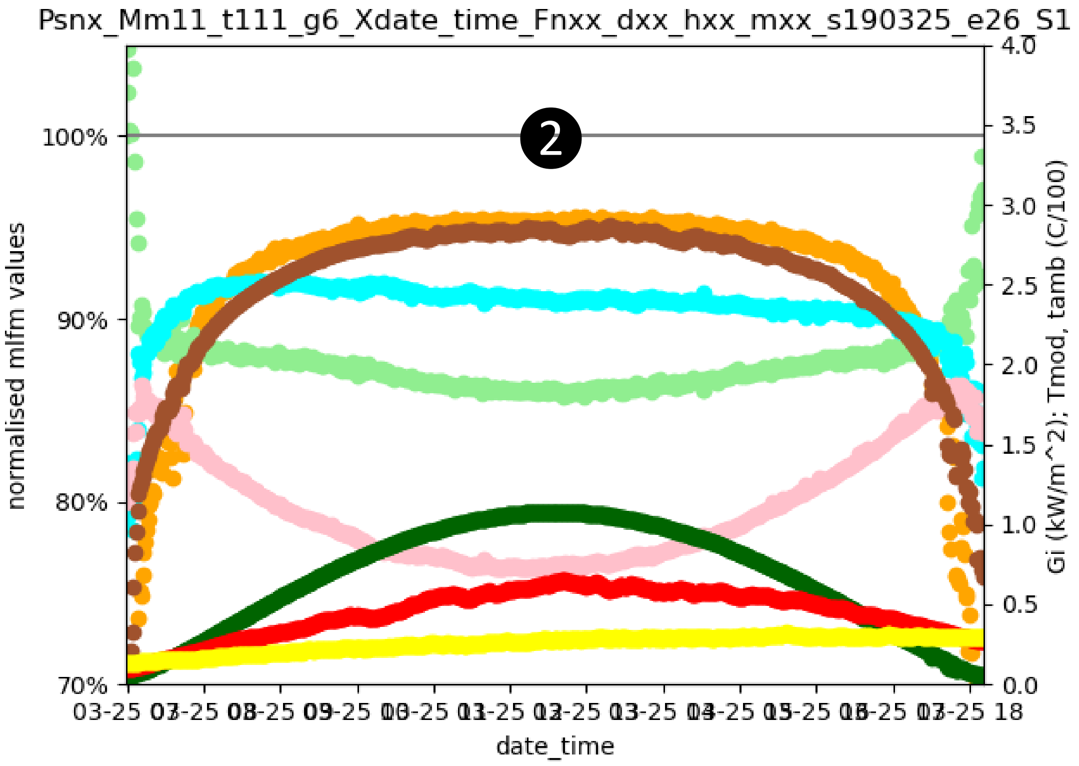
Irrad kW/m²

Tmod C/100

Tamb C/100

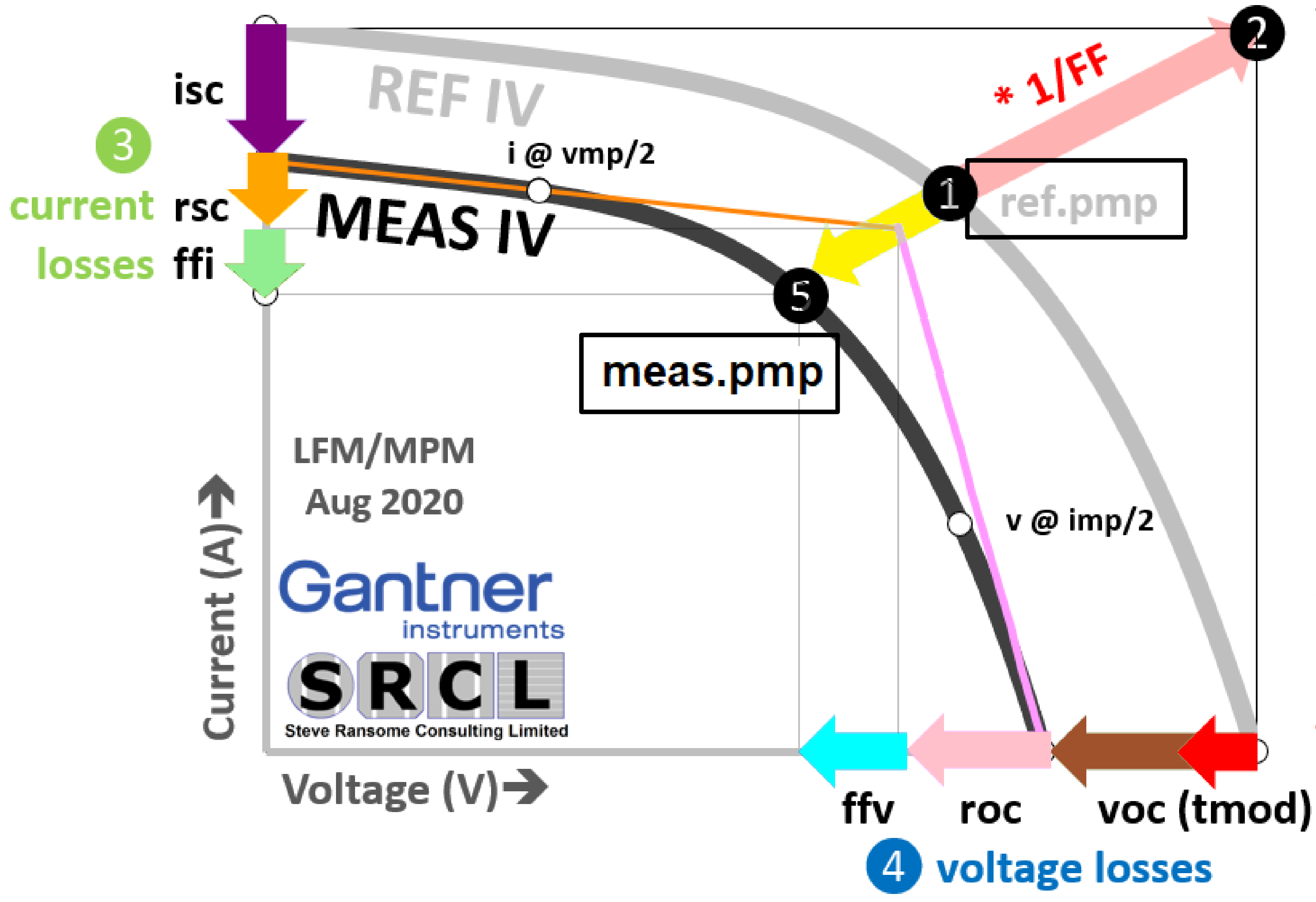
0.7

#11 Thin film
Normalised parameters vs. datetime



Calculating PR_{DC} from the Loss Factors Model (LFM)

PR_{DC} = [Pmax at Point 5] / [Pmax at Point 1]



The LFM extracts normalised, orthogonal losses from IV curves

I_{SC}

R_{SC} (~ Rshunt)

Ffi (Fill Factor ~Current)

Ffv (Fill Factor ~Voltage)

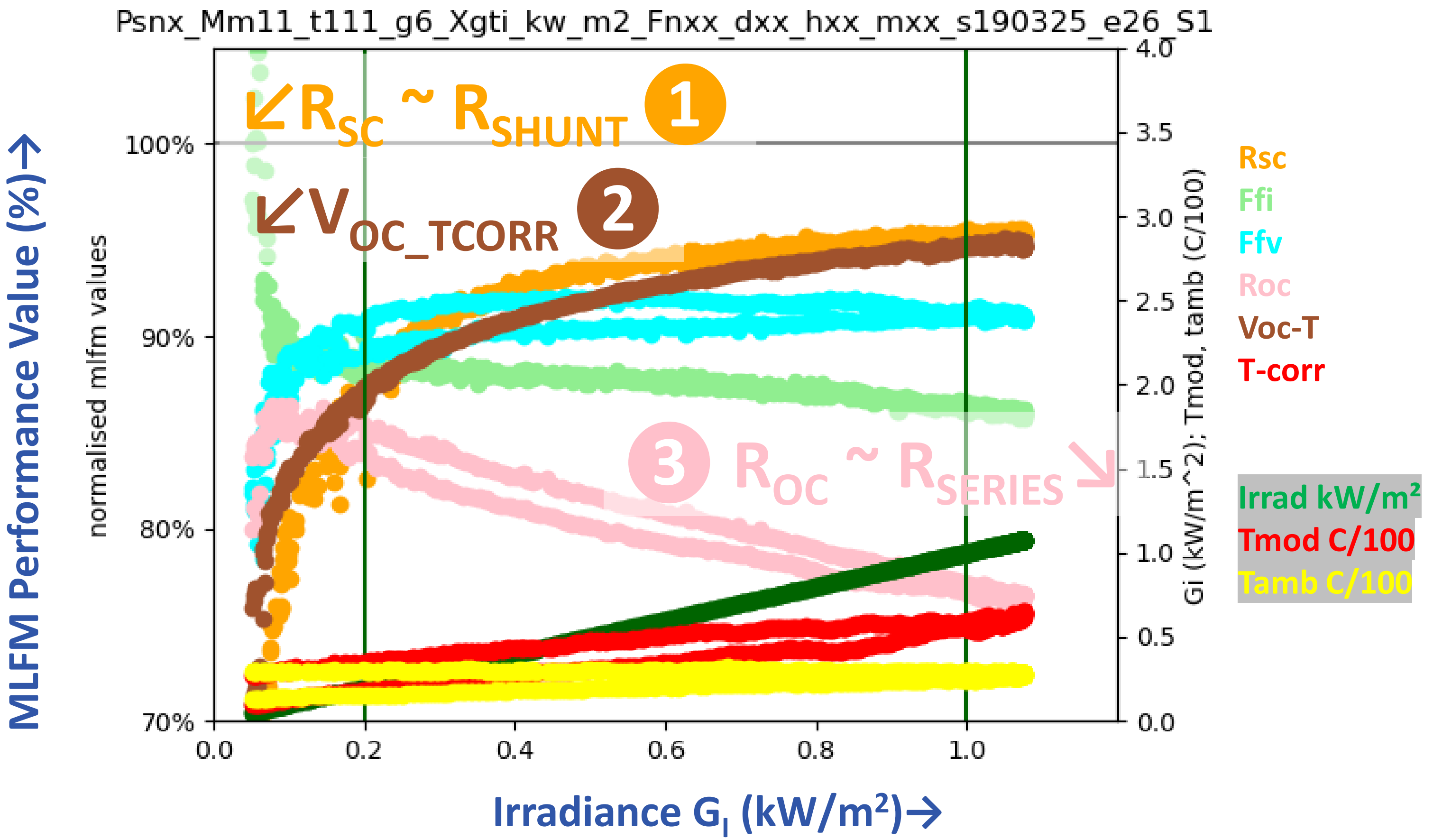
R_{OC} (~ Rseries)

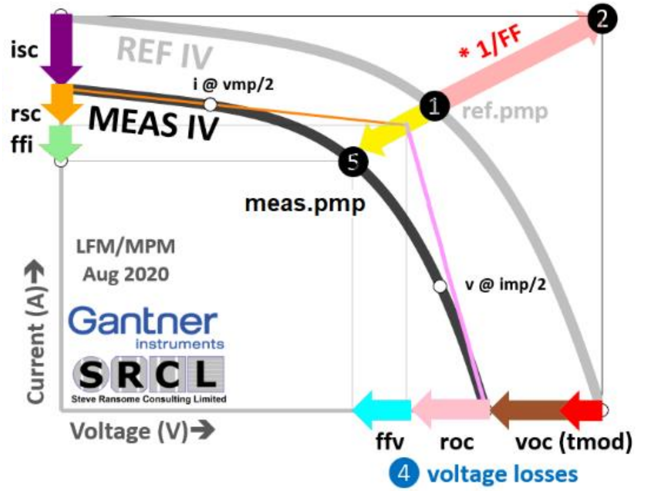
V_{OC} (Temperature corrected)

$T\text{-}_{corr}$ Temperature losses

LFM vs. irradiance identify performance limits and changes

PRdc ∝ 1/FF_ref * norm[(~~isc~~ * rsc * ffi) * (ffv * roc * voc_Tcorr * t_corr)]





The shape of PR_{DC} vs. irradiance is mainly determined by drops in 3 coefficients

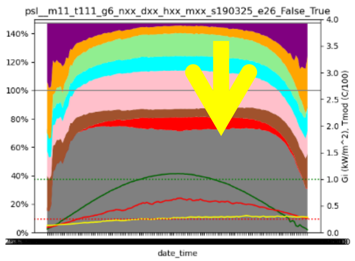
R_{SC} at low light↙

V_{OC} at low light↙

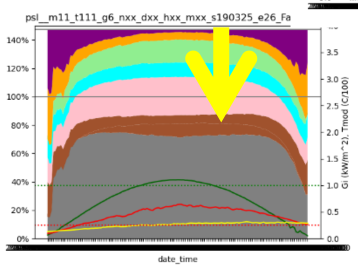
R_{OC} at high light↘

Characterising losses that determine PRdc vs. time 1 day clear sky

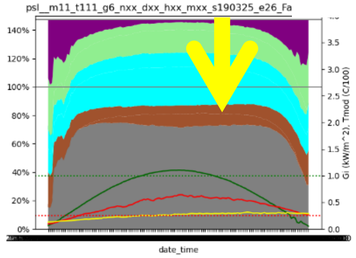
More measurements ↗



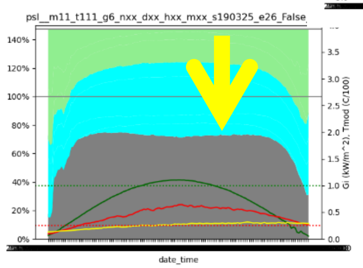
← 7 Isc,Rsc,FFi, FFv,Roc,VocT,Tcorr



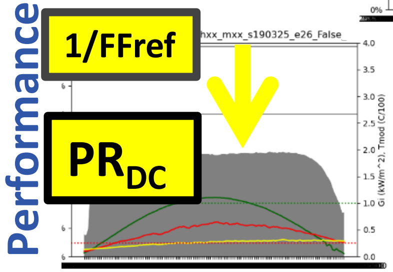
← 6 Isc,Rsc,FFi,FFv,Roc,Voc



← 4 Isc,Imp,Vmp,Voc



← 2 Imp,Vmp (MPPT)



(1 day) Time →

← 1 Only Pmp

$$PR_{DC} = P_{MP.MEAS} / P_{MP.REF} / Gi(kW/m^2)$$

More detailed measurements allow better identification of performance causes vs. irradiance, module temperature and change rates

Visualising LFM losses causing measured behaviour from 1/FF → PR_{DC}

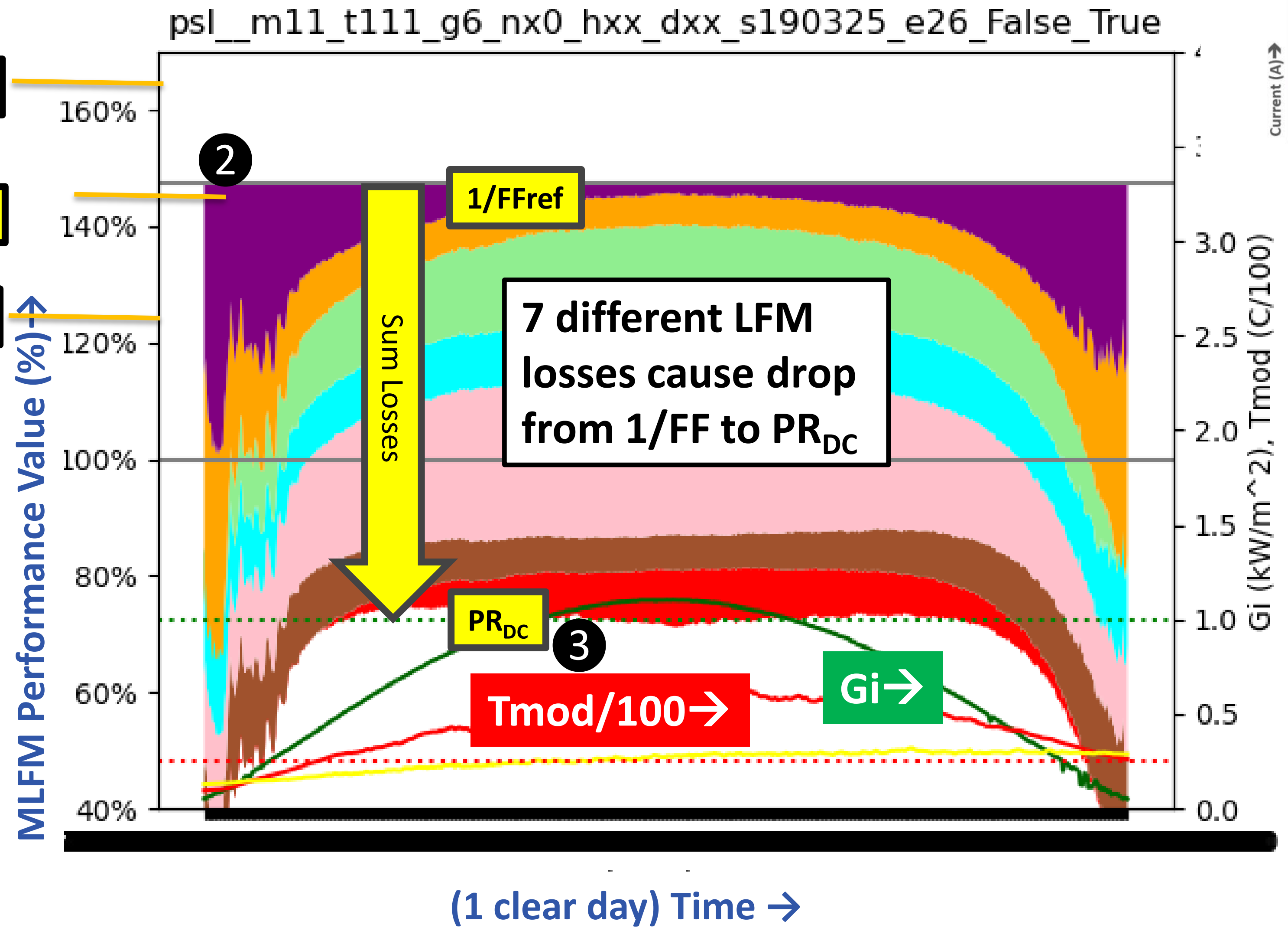
Lossless starts at 1/FF.

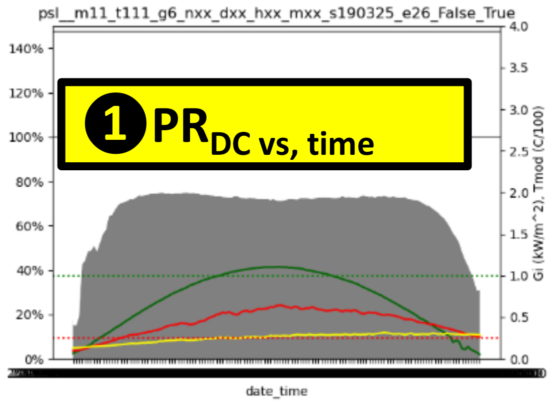
Heights are shown for FF 0.6 to 0.8

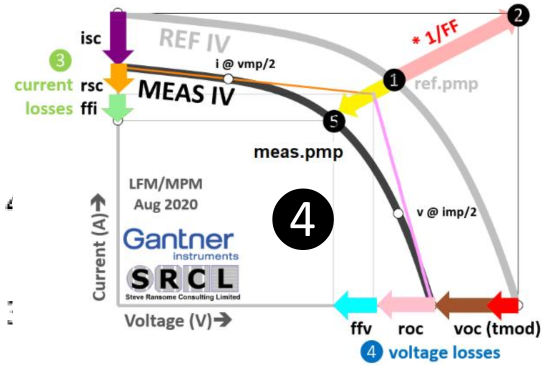
FF~0.6

FF~0.7

FF~0.8







KEY

Isc

Rsc

Ffi

Ffv

Roc

Voc-T

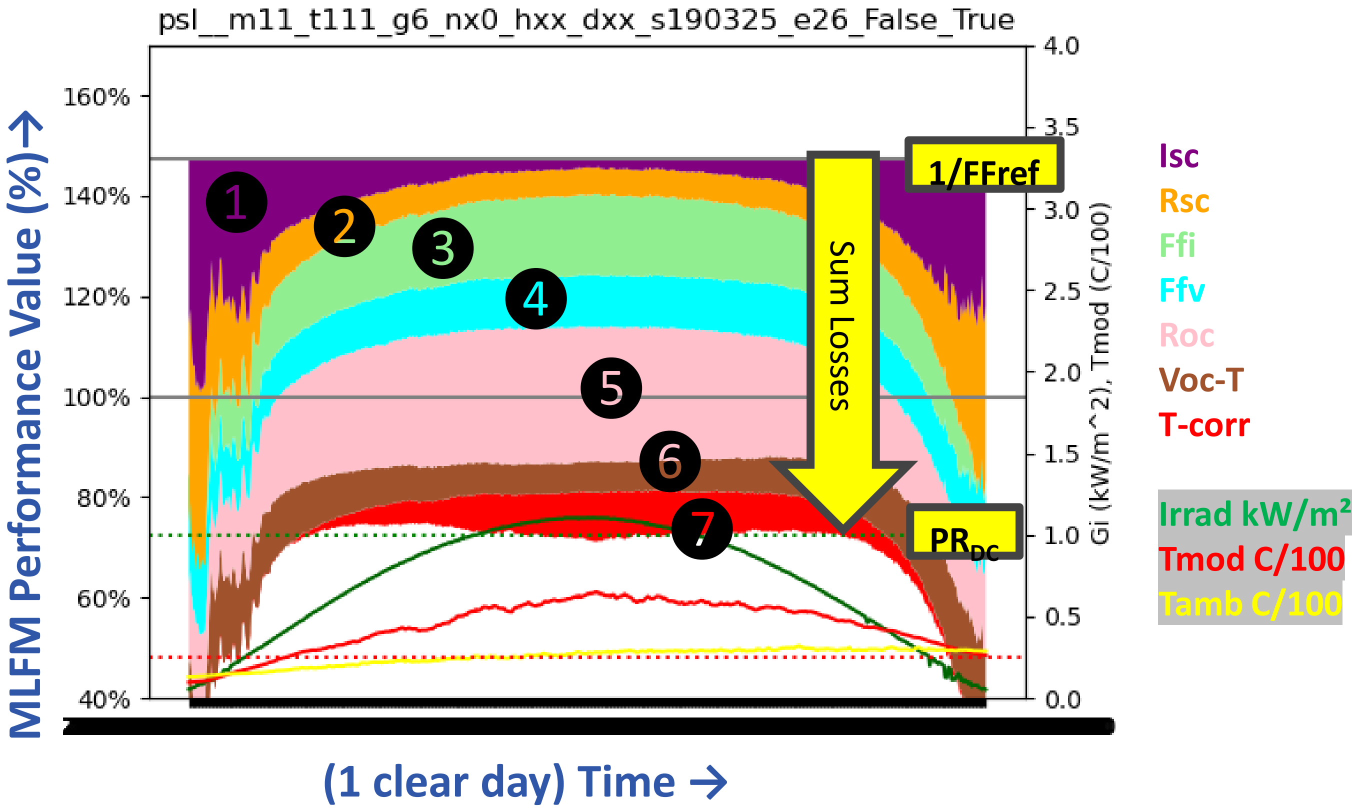
T-corr

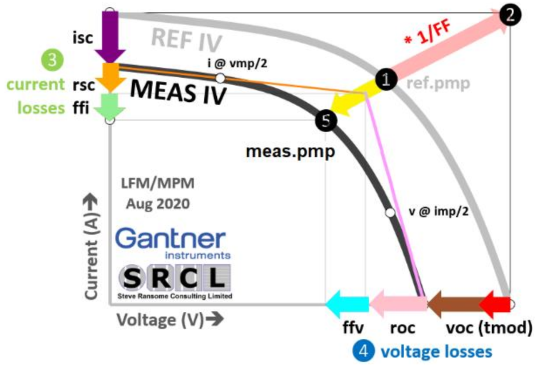
Irrad kW/m²

Tmod C/100

Tamb C/100

Stacked performance losses 1 clear day from 1/FF → PR_{DC}





1 I_{SC} loss worst morning and evening (AOI reflection and/or spectral) scatter due to transmission lines shading early morning

2 R_{SC} (shunt) loss worst morning and evening at low light

3 Fill Factor ~Current ~ constant

4 Fill Factor ~Voltage ~ constant

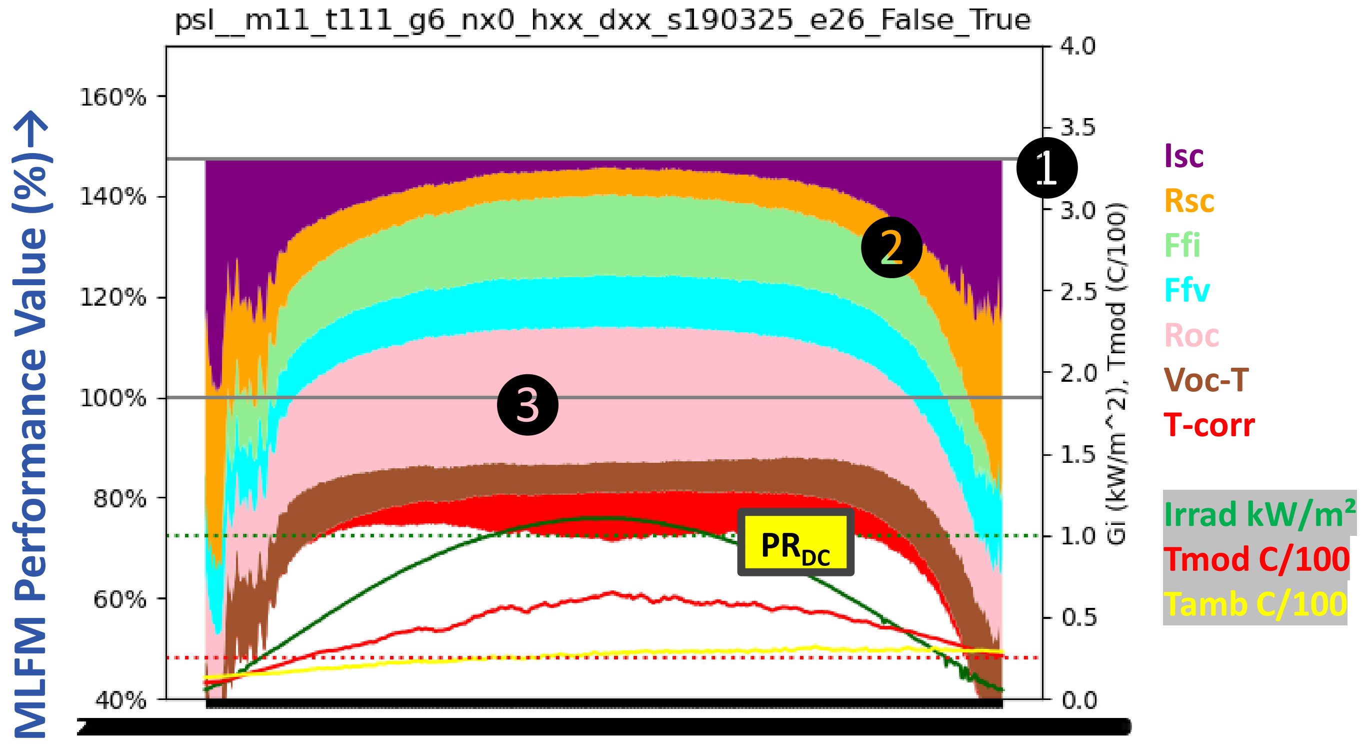
5 R_{OC} (series) loss worst mid day at high irradiance

6 V_{OC} (temperature corrected loss) is worst at lower light levels

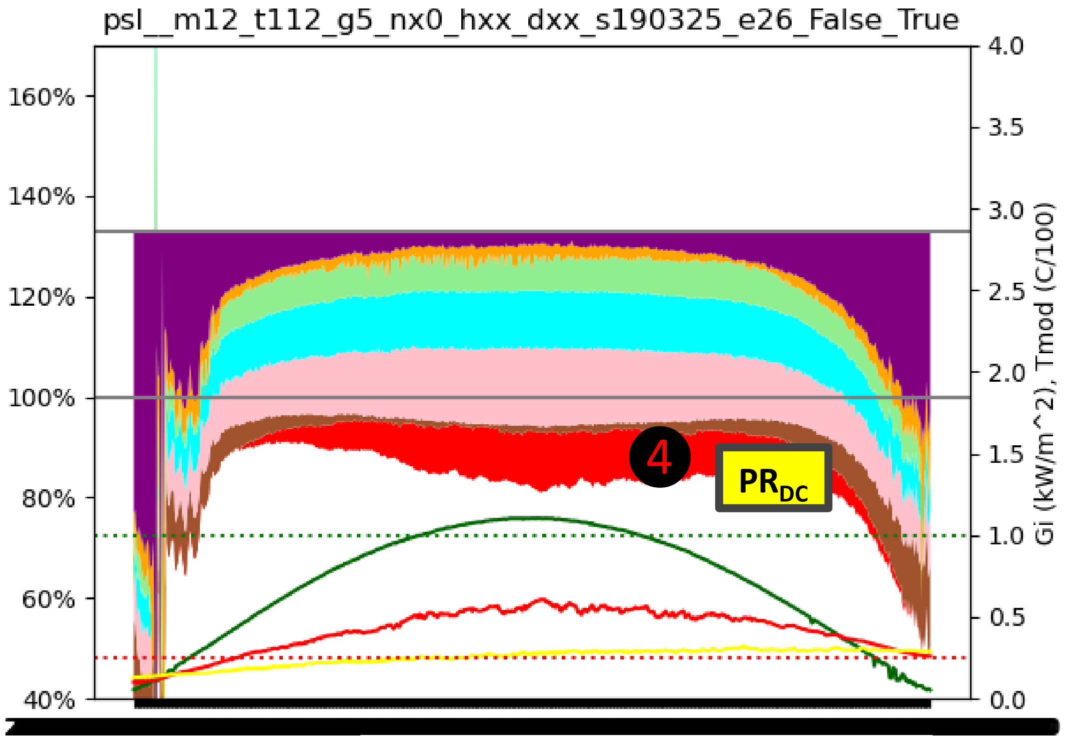
7 $T\text{-}_{corr}$ Temperature losses highest in the afternoon

Stacked performance losses 1 day vs. technology

#11 Thin film



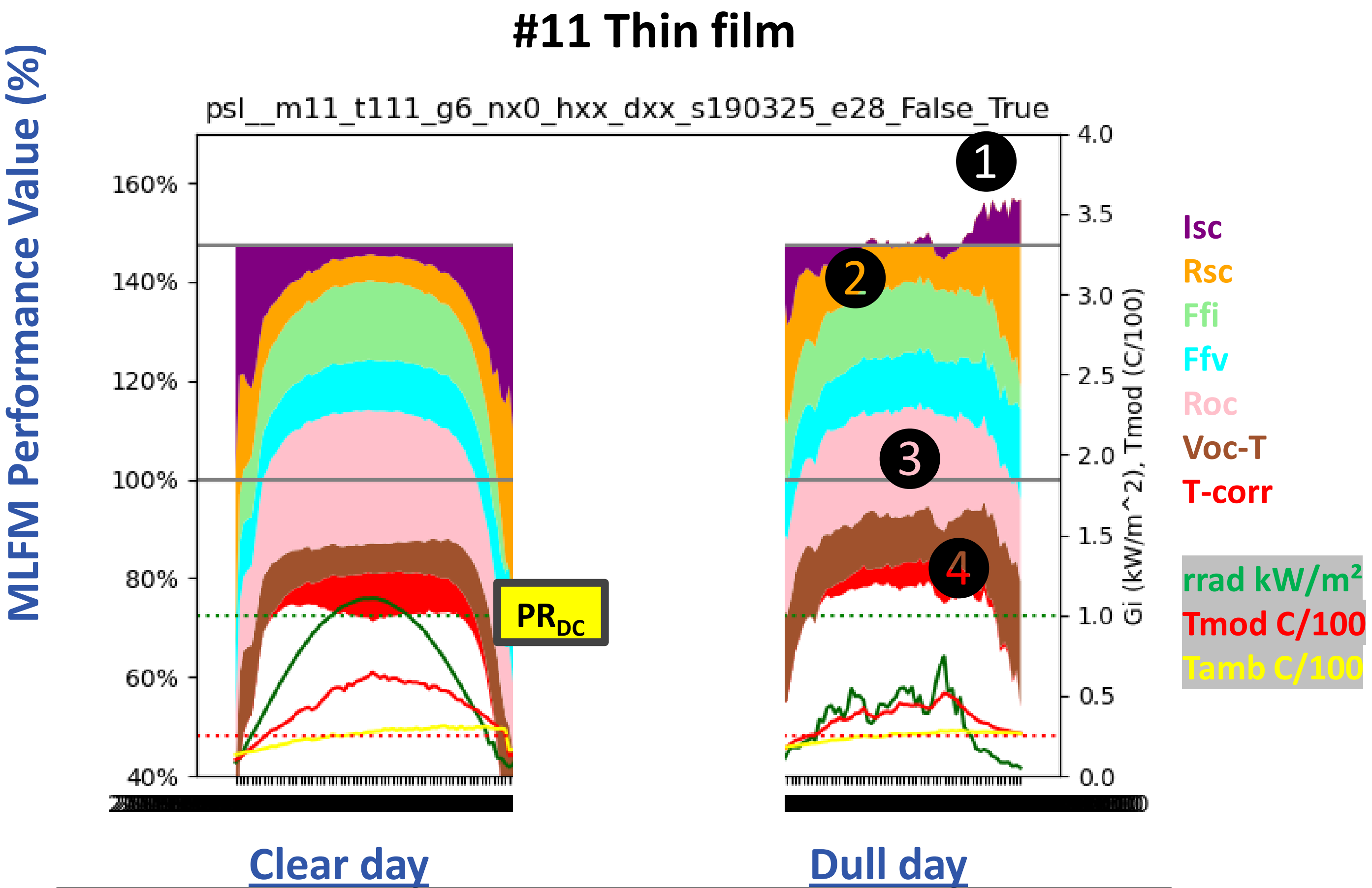
12 cSi



1 Starts higher (1/ff)
2 worse Rsc and 3 Roc losses than cSi

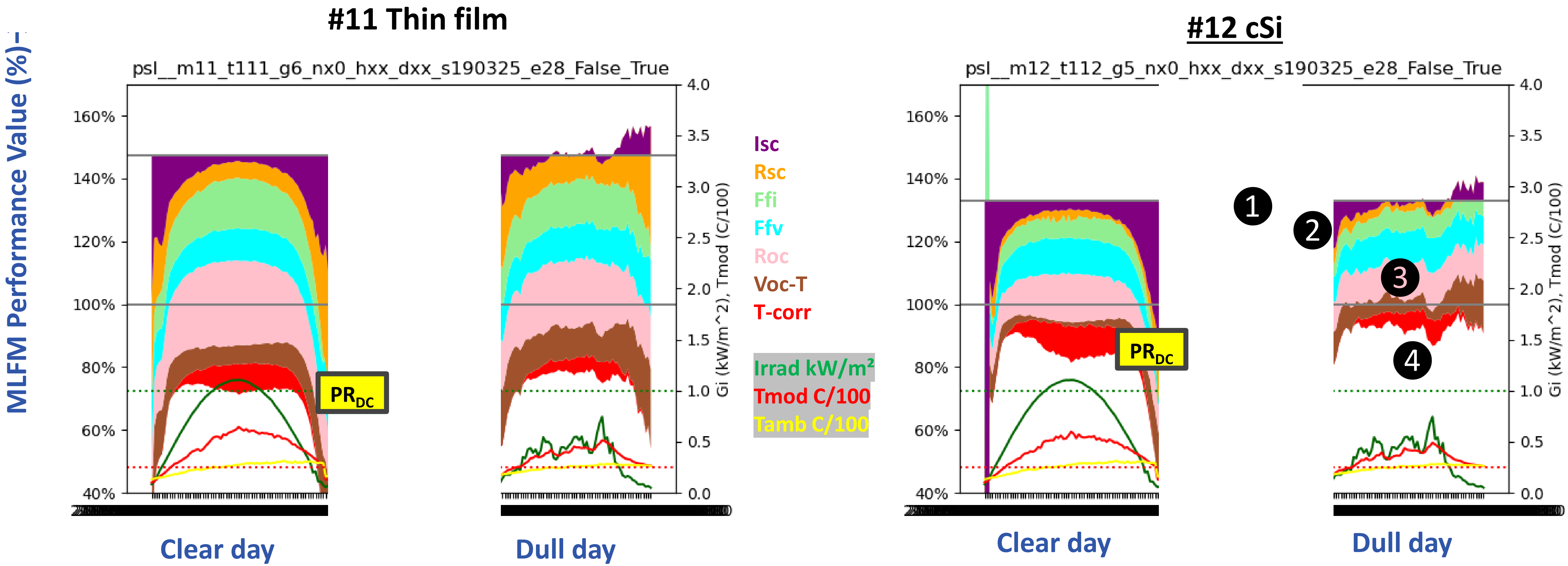
Starts lower (1/ff), better Rsc and Roc losses but worse 4 temperature loss

Stacked performance losses vs. clear (left) and cloudy (right) weather



Cloudy vs. Clear : 1 Isc gain under cloudy blue skies 2 worse Rsc 3 better Roc and 4 better Temperature losses

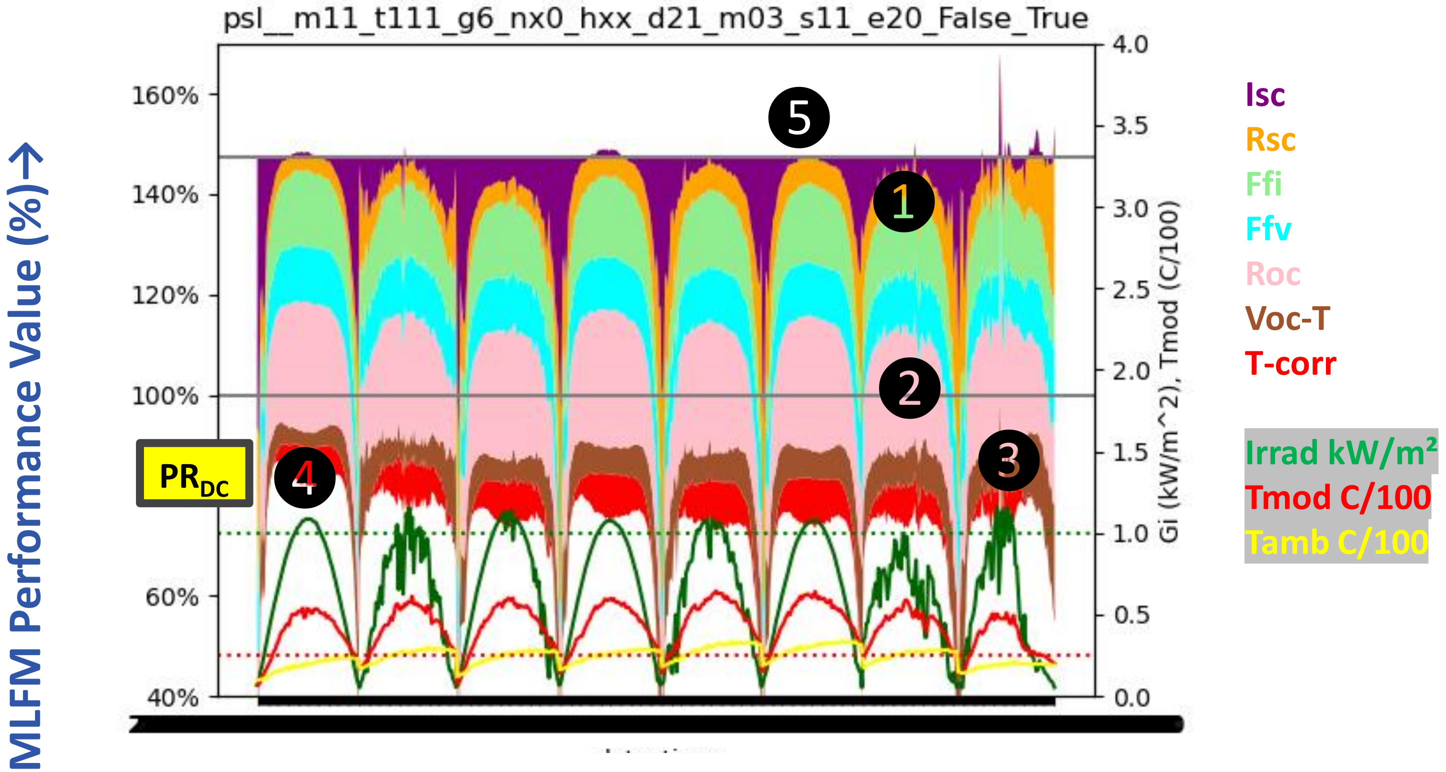
Stacked performance losses vs. clear (left) and cloudy (right) weather



❶ Starts lower (1/ff) then better ❷ Rsc and ❸ Roc losses than thin film but worse ❹ temperature loss

Long term stacked performance losses >7 years

#11 Thin film



2012 **2019**

(1 March day each year)

Losses change per day each year

❶ R_{SC} (shunt) loss increasing with time

❷ R_{OC} (series) loss increasing with time

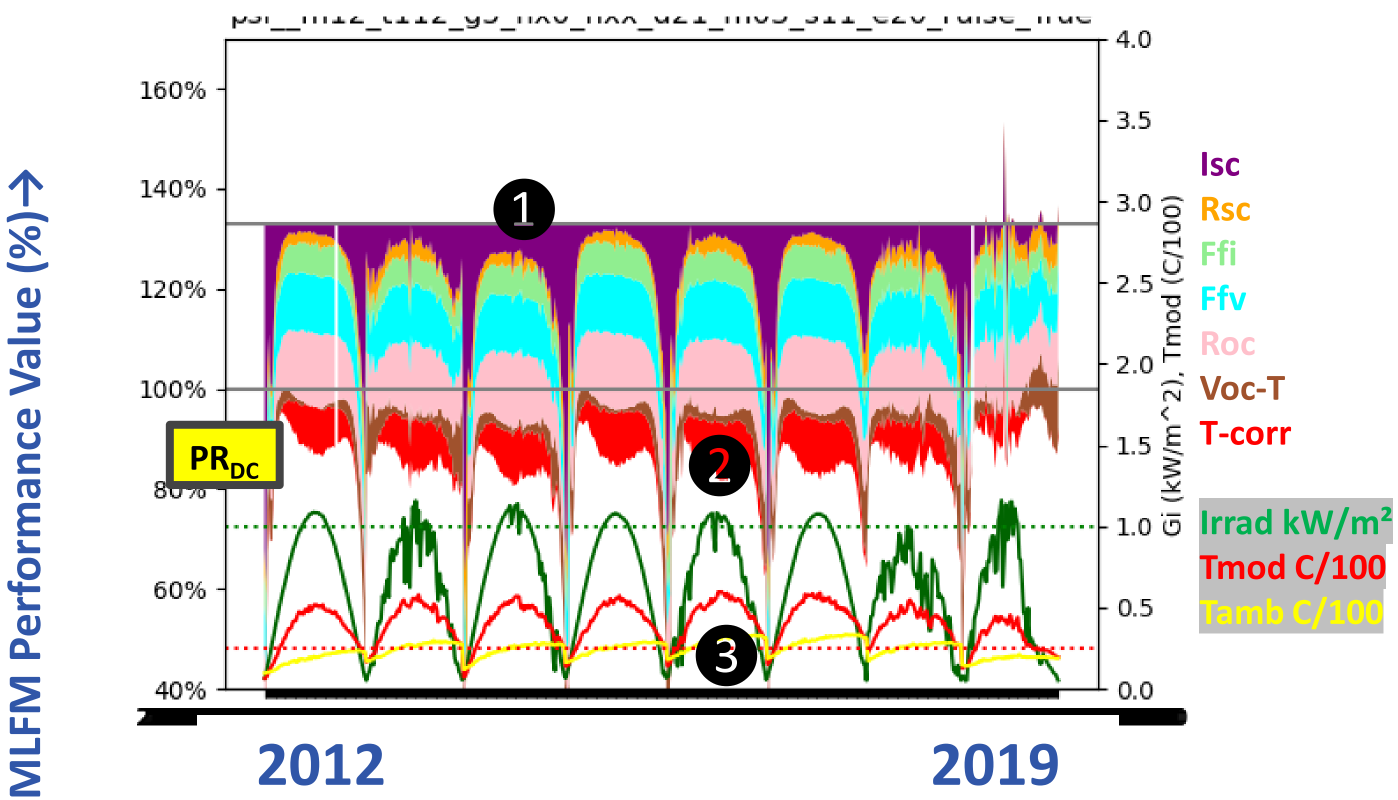
❸ V_{OC} (temperature corrected loss) increasing with time

❹ **PR_{DC}** fall mainly caused by these 3 parameters

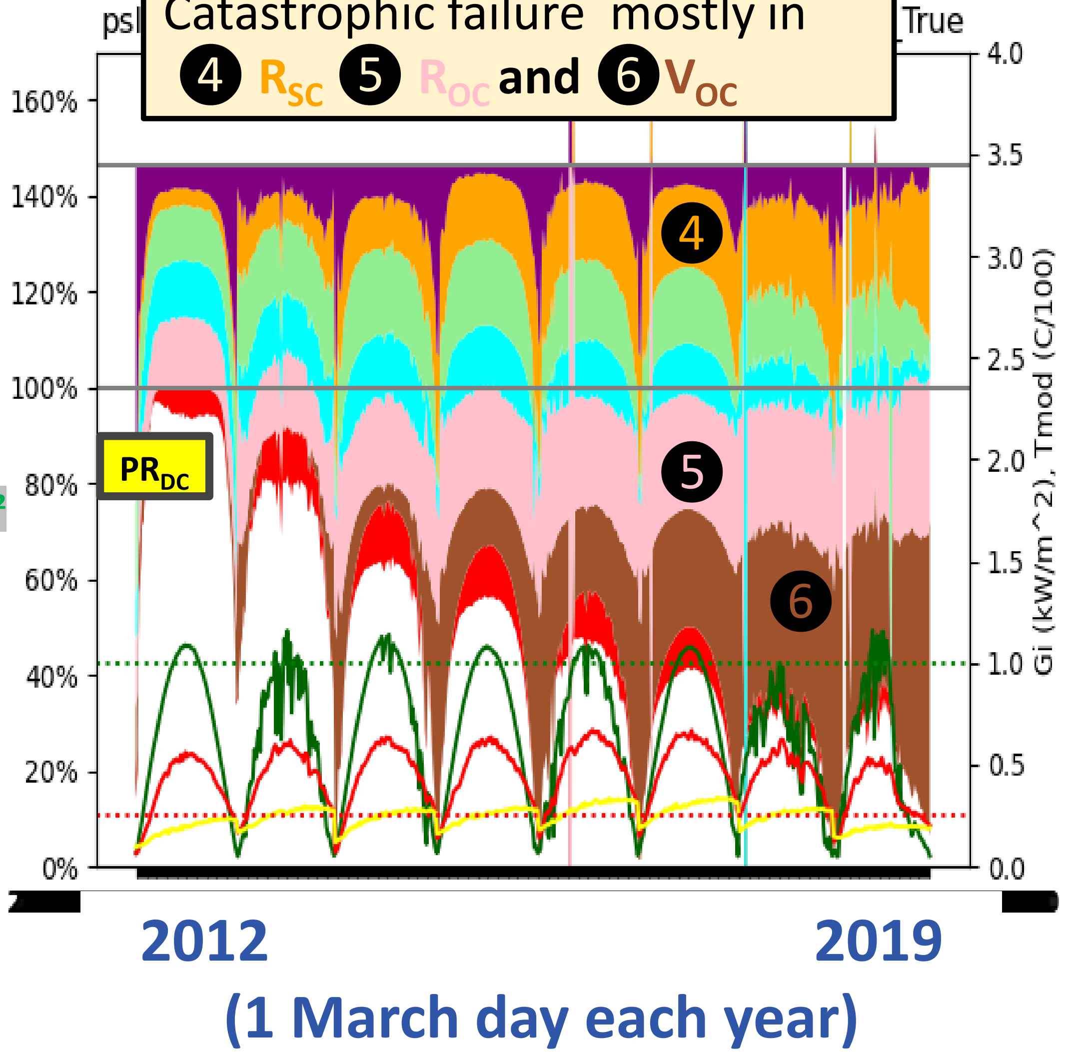
❺ Maybe soiling causing variable I_{SC} loss (can self reference to get smoother plots of other parameters)

Long term stacked performance losses >7 years vs. Technology (cSi and failed)

#12 cSi



#15 Failed Thin Film
Catastrophic failure mostly in
4 R_{SC} 5 R_{OC} and 6 V_{OC}

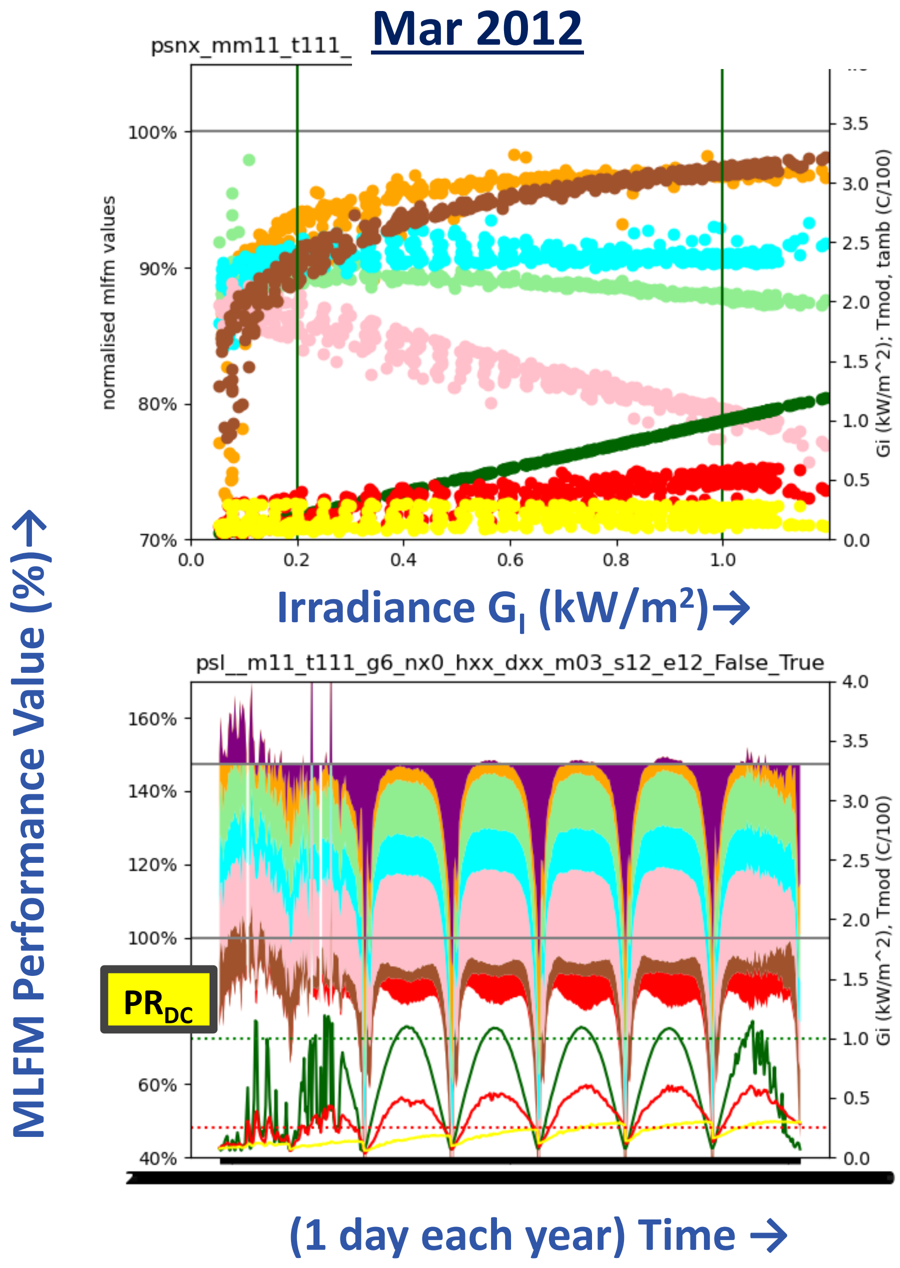


1 Soiling variation?
2 PR_{DC} stable similar weather,
3 note dependence on module temperature

Analysing changes between two dates

#11 thin film between 2012,2017

7 days



Characterise module performance with a few days of variable weather

Then look for differences …

Isc
Rsc
Ffi
Ffv
Roc
Voc-T
T-corr

Irrad kW/m²
Tmod C/100
Tamb C/100

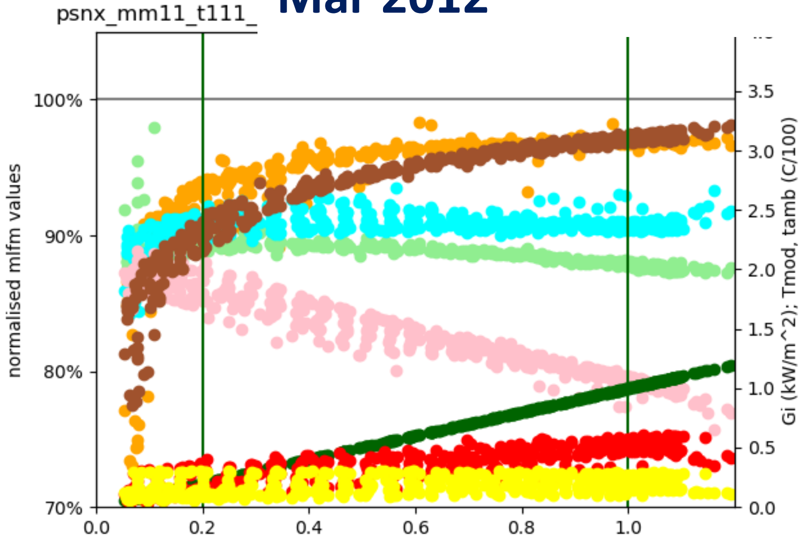
Analysing changes between two dates

#11 thin film between 2012,2017

7 days

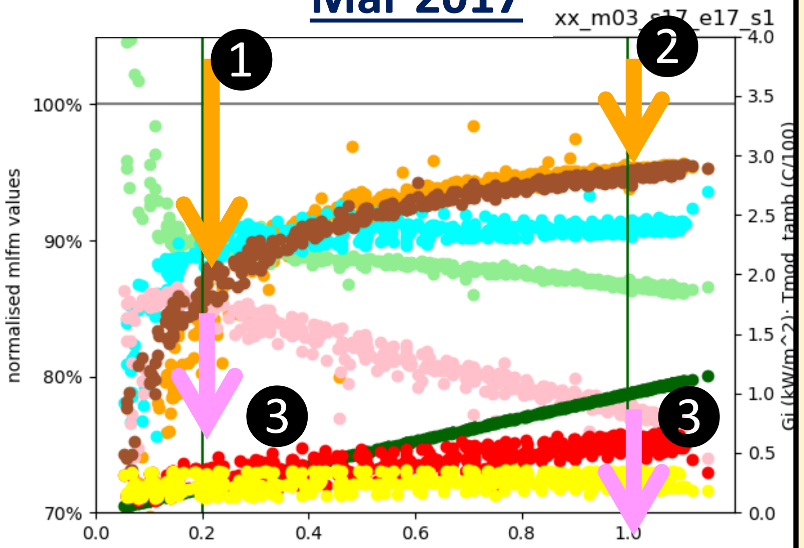
MLFM Performance value (%)→

Mar 2012

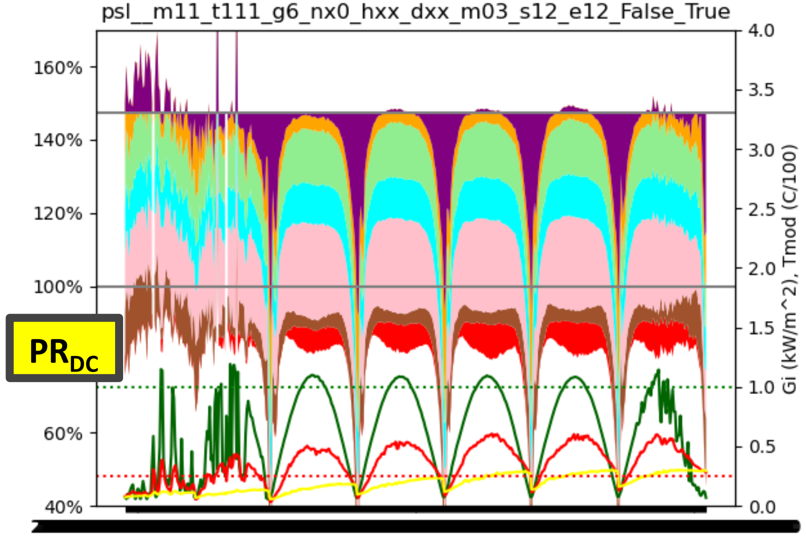


Irradiance G_I (kW/m²)→

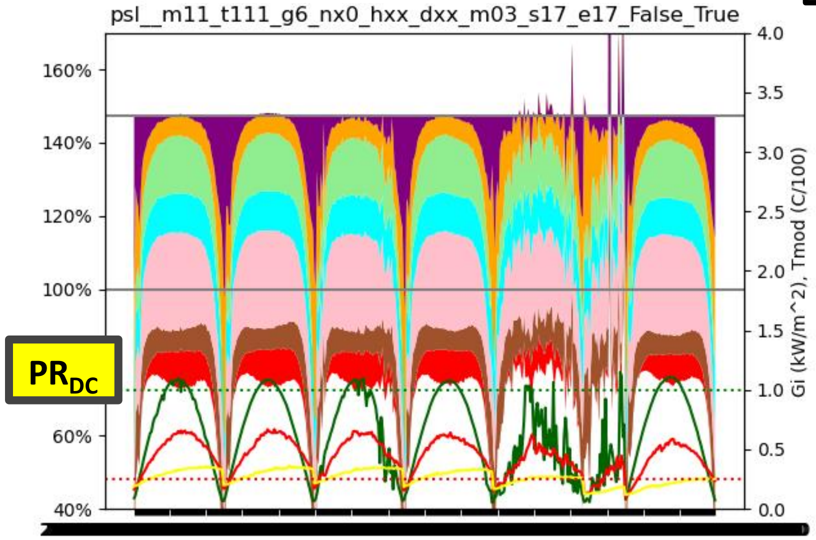
Mar 2017



Irradiance G_I (kW/m²)→



(1 day each year) Time →



(1 day each year) Time →

Degradation

R_{SC} falls faster at ❶ low light levels than high light levels ❷

R_{OC} falls constant ❸ with light level

Isc
Rsc
Ffi
Ffv
Roc
Voc-T
T-corr

Irrad kW/m²
Tmod C/100
C/100

Gantner instruments

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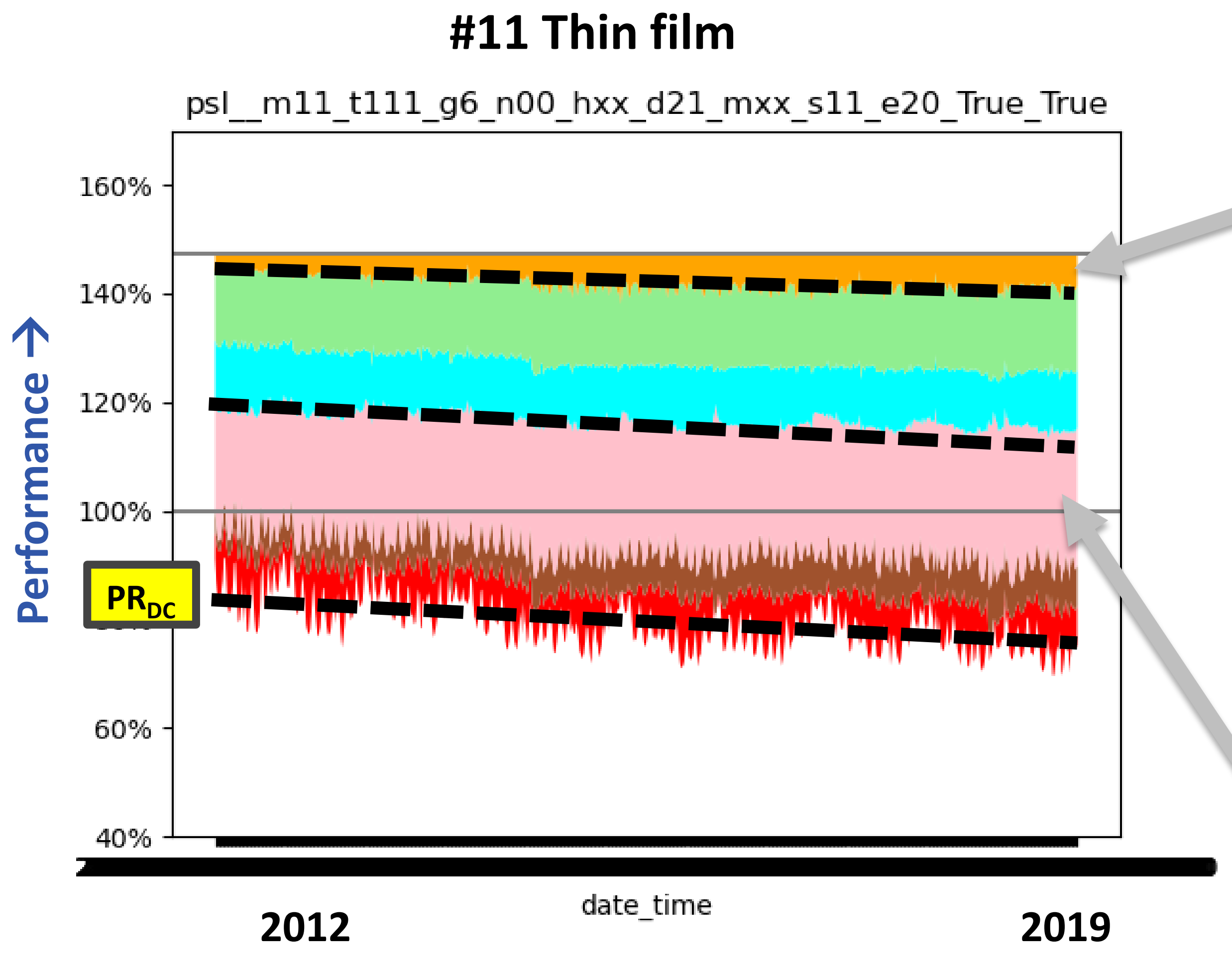
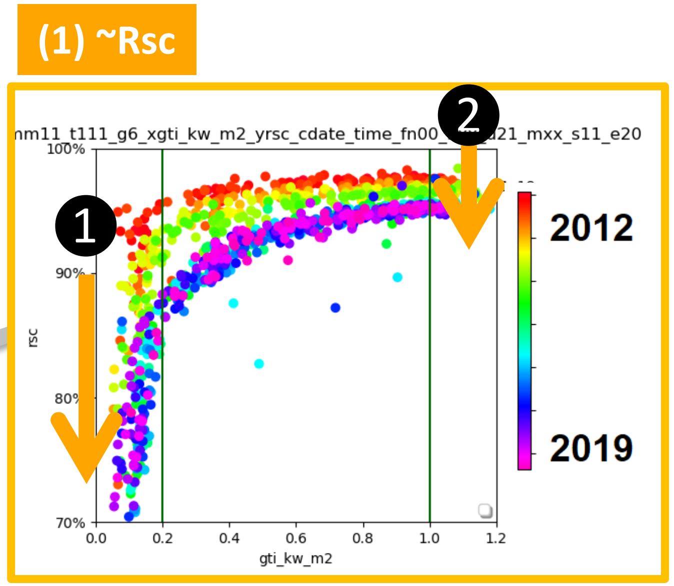
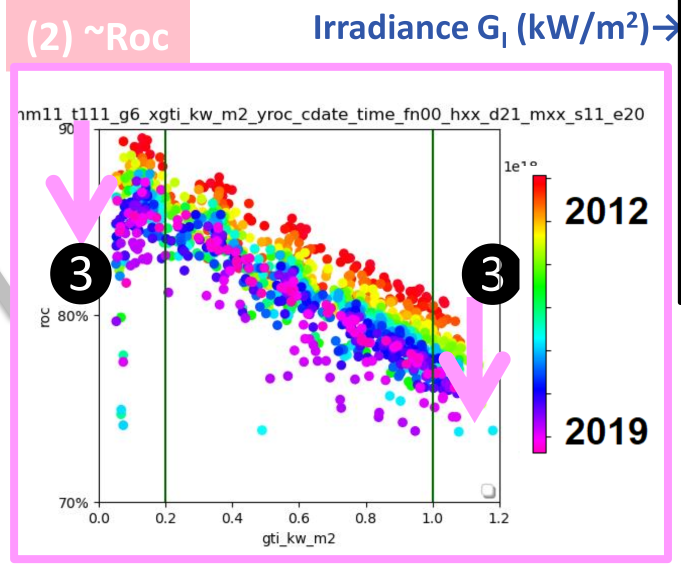
SRCL Steve Ransome Consulting Limited

Stacked loss graphs can qualify and quantify any long-term degradation –

Gantner 2012-2019 (self referenced Isc) Unstable







Degradation

R_{SC} falls faster at 1 low light levels than high light levels 2

R_{OC} falls constant 3 with light level

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

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

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

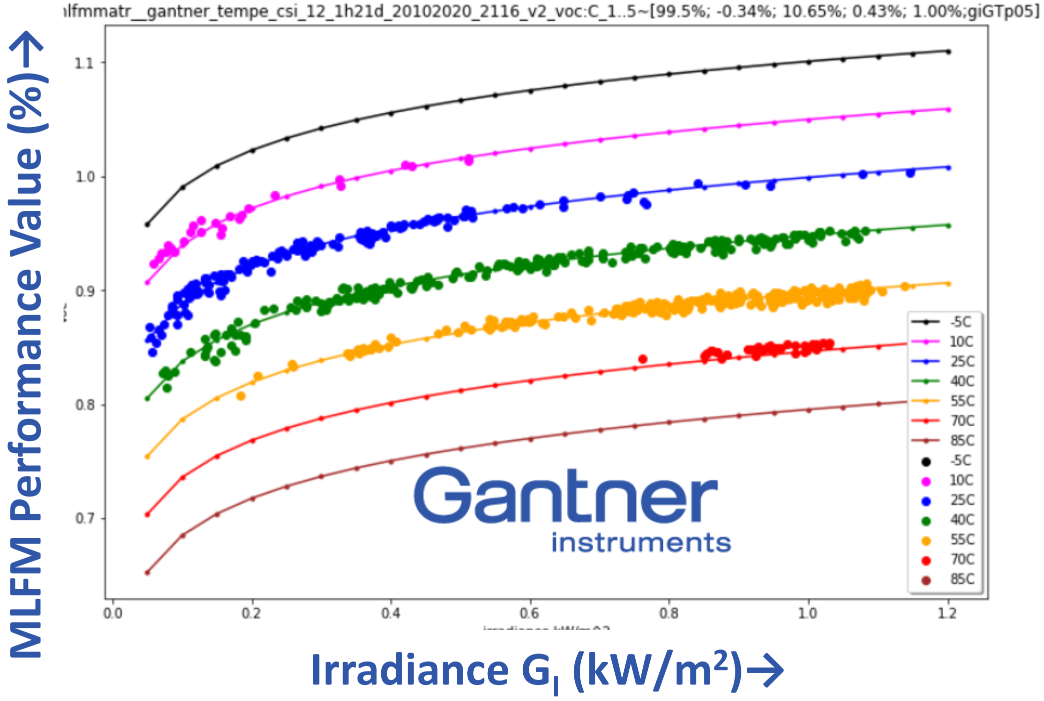
Mechanistic Performance Model –location and technology independent

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

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

- 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})

Reference : PVSC46_Chicago.pdf

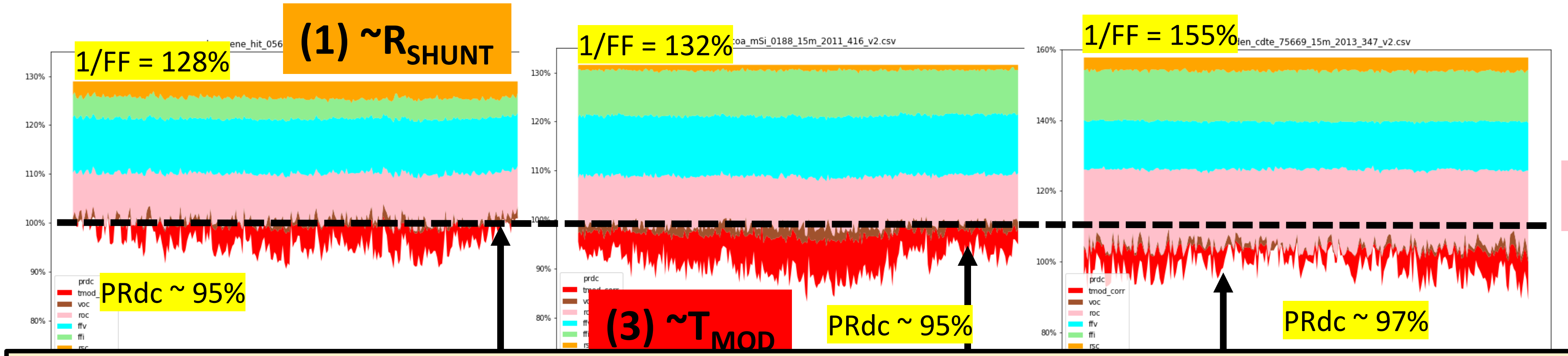


Predicted (lines) vs. Measured (dots)
LFM values fitted with MPM
(7 years cSi module in Tempe AZ)

We don't have time to discuss the fitting methodology in this talk,
also angle of incidence and spectral correction
please contact me or look at previous papers for details

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

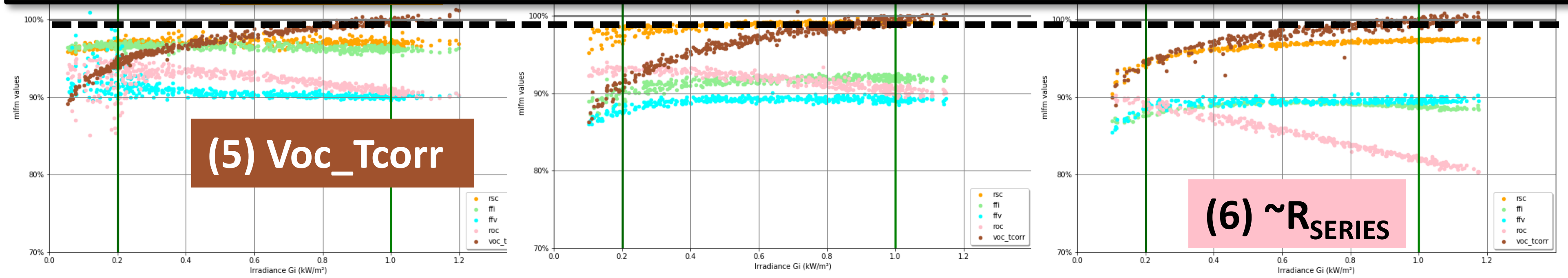
Eugene HIT 01/2013 to 12/2013 | Cocoa mSi 02/2011 to 01/2012 | Golden CdTe 09/2012 to 08/2013 | NREL



Algorithms also tested with NREL Data

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

[Virtual presentation](https://pvpmc.sandia.gov/download/7879/) **https://pvpmc.sandia.gov/download/7879/**



Irradiance G_I (kW/m²)→ | Irradiance G_I (kW/m²)→ | Irradiance G_I (kW/m²)→

Summary

- Good quality data required for best understanding

- Graphical analysis shown of stacked losses to find cause of any underperformance and quantify degradation

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

- Methodology is being introduced to Gantner Instruments OTF, cloud based Performance services and digital twins

- Feedback welcome !

Contact

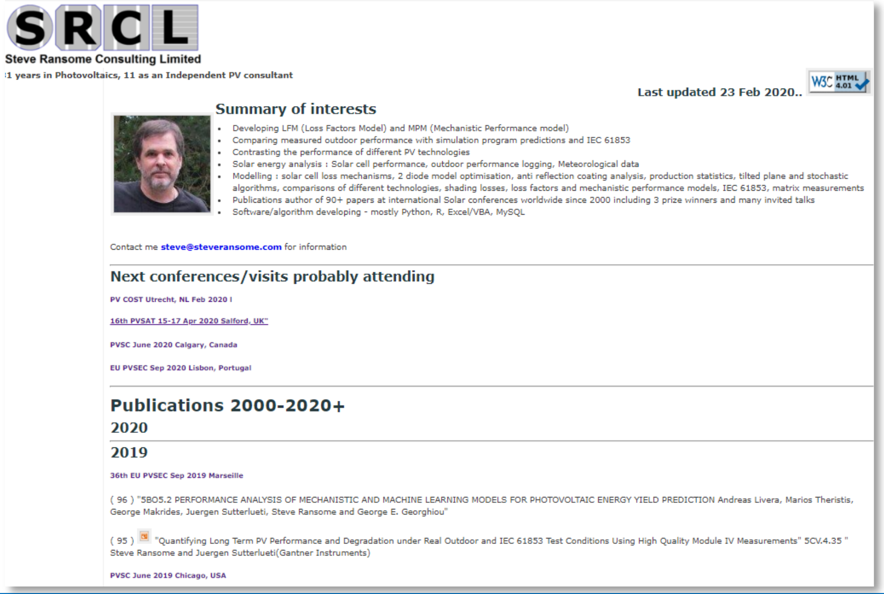
Steve Ransome (SRCL, UK) www.steveransome.com ; [mailto: steve@steveransome.com](mailto:steve@steveransome.com)

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



SRCL
Steve Ransome Consulting Limited
:1 years in Photovoltaics, 11 as an Independent PV consultant

Last updated 23 Feb 2020..

Summary of interests

- Developing LFM (Loss Factors Model) and MPM (Mechanistic Performance model)
- Comparing measured outdoor performance with simulation program predictions and IEC 61853
- Contrasting the performance of different PV technologies
- Solar energy analysis : Solar cell performance, outdoor performance logging, Meteorological data
- Modelling : solar cell loss mechanisms, 2 diode model optimisation, anti reflection coating analysis, production statistics, tilted plane and stochastic algorithms, comparisons of different technologies, shading losses, loss factors and mechanistic performance models, IEC 61853, matrix measurements
- Publications author of 90+ papers at international Solar conferences worldwide since 2000 including 3 prize winners and many invited talks
- Software/algorithm developing - mostly Python, R, Excel/VBA, MySQL

Contact me steve@steveransome.com for information

Next conferences/visits probably attending

PV COST Utrecht, NL Feb 2020 !

16th PVSAT 15-17 Apr 2020 Salford, UK"

PVSC June 2020 Calgary, Canada

EU PVSEC Sep 2020 Lisbon, Portugal

Publications 2000-2020+

2020

2019

36th EU PVSEC Sep 2019 Marseille

(96) "5BO5.2 PERFORMANCE ANALYSIS OF MECHANISTIC AND MACHINE LEARNING MODELS FOR PHOTOVOLTAIC ENERGY YIELD PREDICTION Andreas Livera, Marios Theristis, George Makrides, Juergen Sutterlueti, Steve Ransome and George E. Georghiou"

(95) "Quantifying Long Term PV Performance and Degradation under Real Outdoor and IEC 61853 Test Conditions Using High Quality Module IV Measurements" 5CV.4.35 " Steve Ransome and Juergen Sutterlueti(Gantner Instruments)

PVSC June 2019 Chicago, USA

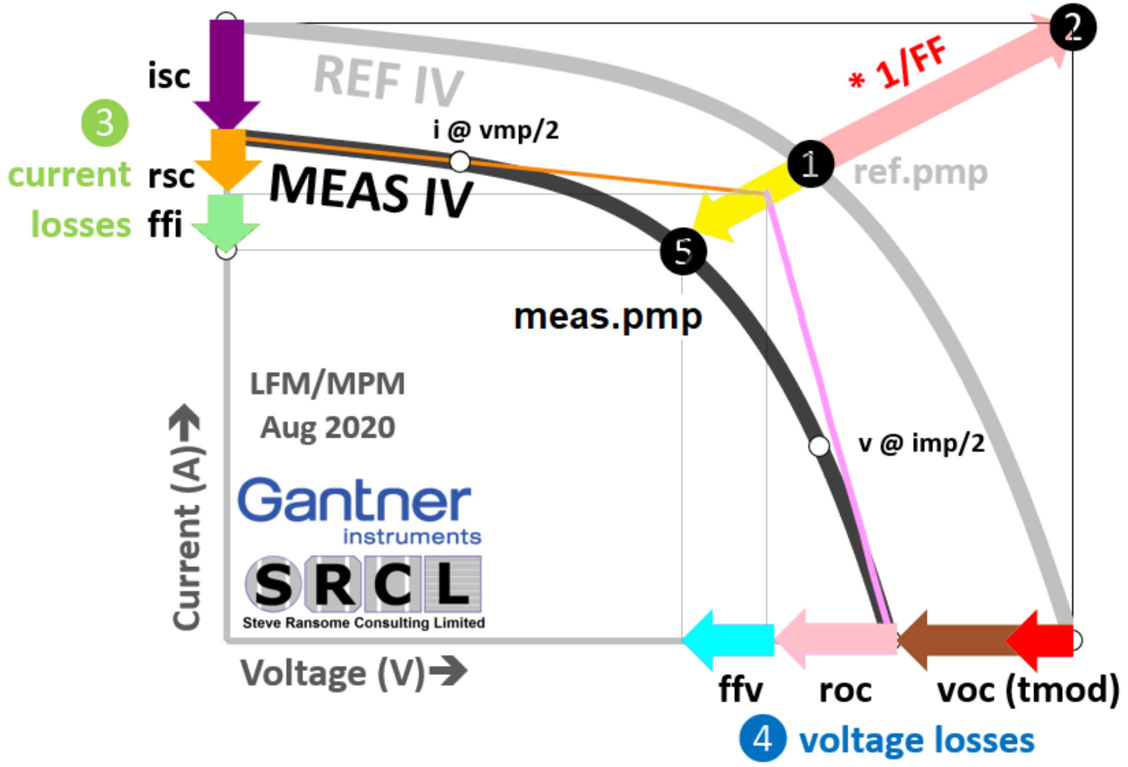
All papers are either available through SRCL website or writing to me directly

SPARE

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